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Lateral Migration of the Red River, in the Vicinity of Grand Forks, North Dakota

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1. *Abstract*

River channels are dynamic landforms that play an important role in understanding the alluvial changes occurring within this area. The evolution of the Red River of the North within the shallow alluvial valley was investigated within a 60 river mile area north and south of Grand Forks, North Dakota. Despite considerable research along the Red River of the North, near St. Jean Baptiste, Manitoba, little is known about the historical channel dynamics within the defined study area. A series of 31 measurements were taken using three separate methods to document the path of lateral channel migration along areas of this highly sinuous, low- gradient river. Specifically, historical aerial photographs, cross sectional elevation based models, and PLAT maps were used to determine how the river channel has laterally migrated over the past 142 years. Locations of the measurements were dependent upon availability of data within each specified method, as measurements were only taken from where movement could be seen and documented. Results from these methods indicate that the channel has undergone noticeable changes in some regions of the river. The maximum migration distance of this river found using cross sectional data is 1455.42 meters, and is seen by re- occurring oxbows and scars throughout the broad flat valley. Utilizing all three methods within the study area, it is found that rates are averaging between 0.01 and 0.38 meters/ year. This shows a maximum distance of lateral migration of 54.4 meters over the span of 142 years, and implies that the low energy, mud- dominated river is undergoing long-term, lateral migration at a low rate. Overall, these results provide important context for assessing whether similar patterns and rates of channel migration exist throughout the Red River of the North. Viewing these low rates found throughout the study area shows no potential risk or harm to the city's infrastructure within the next 100 years.

2. Introduction and Motivation

Considerable interest exists to understand the Red River's lateral migration throughout the Red River Valley. This research focuses on the channel migration of the Red River of the North, specifically past orientations of the rivers course in the vicinity of Grand Forks, ND.

By examining the fluvial systems of the main channel, a closer look can be taken at the channel patterns in relation to hydrologic characteristics. Research by Giardino and Lee (2011) discusses the impact of changes in hydrologic discharge on the rates and styles of lateral channel migration. Highest migration rates occur when total discharge is at its highest, suggesting that as well as gradient, total surface discharge within the channel is one of few factors that need to be considered when determining migration rates.

The migration rates of large sinuous alluvial rivers have received a great deal of attention in the fields of geomorphology, geology, and engineering (Dunne and Leopold, 1978). The Red River Valley of North Dakota/Minnesota is the youngest major land surface in the contiguous United States, having been sub aerially exposed upon the final regional drainage of Glacial Lake Agassiz around 9,300 years ago. Most river systems in the United States date back millions to tens of millions of years, whereas the present course of the Red River of the North is only a few thousands of years old. This is of great importance when looking at the complexity of a river because this river has had geologically, a shorter time to progress. Studies investigating fluvial geomorphic change over timescales of many thousands of years have provided insights into the long-term temporal character and controls on modern rivers.

Rivers such as the Ninglick River in Newtok, Alaska, is a great example of this. Rapid erosion is occurring throughout many of Alaska's coastlines, forcing communities to relocate as the coastal land continues to vanish. This river is eroding away at the riverbank as much as 22.86 meters per year (75 feet), knocking homes and villages out of alignment (Figure 1). There is a great deal of importance in understanding such processes, and continuing to study and understand migration rates within large fluvial rivers will benefit such communities and infrastructures throughout.

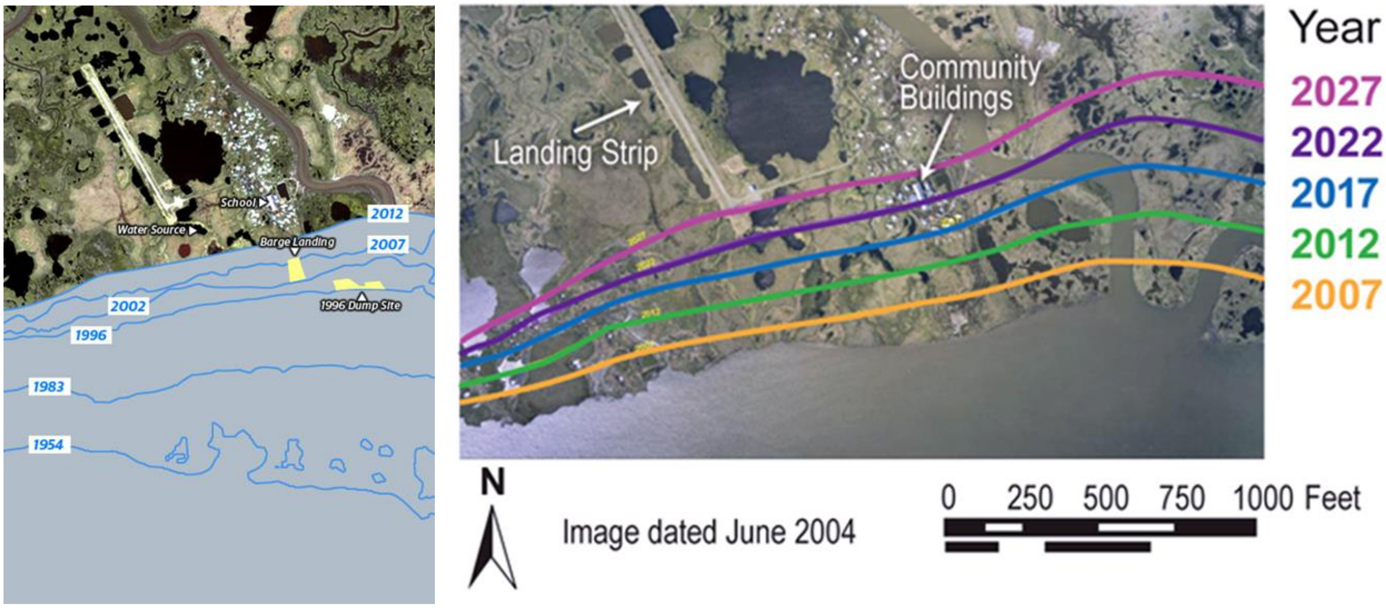


Figure 1. Illustrations showing the significance of channel migration within Newtok, Alaska

Rivers that flow across unconsolidated, fine-grained sediment have a tendency to meander; much like the Red River (Schwert, 2003). Studies of these alluvial systems investigating fluvial geomorphic change over a timescale of many thousands of years can further provide average rates to which this river has migrated.

Channel migration of the Red River is of great importance, especially in this area, as it runs right through several urban populated cities. With such potentially unstable river conditions, the understanding of such migration processes, as well as rates at which it occurs, allows for a more stable infrastructure throughout the cities future planning. The information gathered for this research can lead to a better understanding as to how the course of the Red River has changed over time. With calculating these rates over the past century, a good interpretation can be made of what can be expected in the near future. This is saying that rates remain constant, and with that a general interpretation of the next 100 years can made throughout the city limits and field area.

3. Previous Research

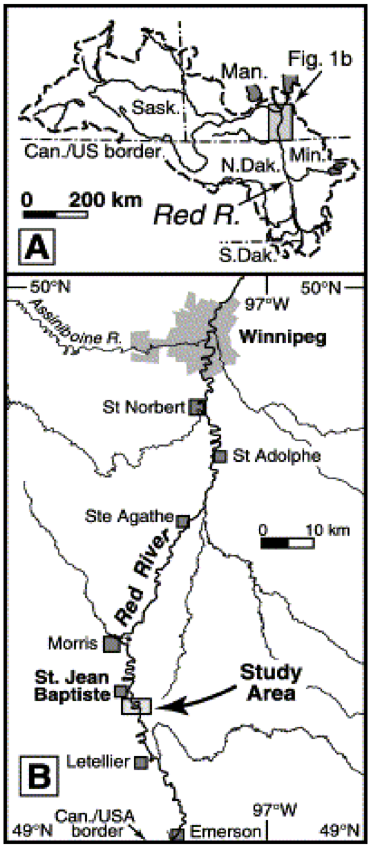
Previous research pertaining to this project can be found within two large categories: satellite aerial imagery and topographic maps integrated into GIS programs for measurement, and the analyzing of alluvial deposits through radio carbon dating and core chronology.

3.1 Radiocarbon dating and core chronology

To asses the importance of fluvial geomorphic changes within the valley, a borehole investigation of the floodplain was undertaken at two successive river meanders located near St. Jean Baptiste on the Red River of the North. The clay plain is composed of glaciolacustrine sediments that aggraded within glacial Lake Agassiz during the late Pleistocene and early Holocene. In Manitoba, the river became established on the lake bed between 7800 and 8200 cal. years B.P. as the lake receded northward. The river has since eroded a shallow valley into the clay plain, that is up to 15 meters deep and 2,500 meters wide and contains the genetic flood plain of the river (Brooks, 2002).

Within Manitoba, the Red River is a single-channeled, meandering river with an irregular sinuosity and a low average valley gradient of 0.0001. The flood plain and the contemporary riverbanks are composed predominantly of silt alluvium, representing an example of a mud-dominated stream. A curvilinear pattern and swale topography commonly marks past channel positions across the valley bottom, and reveals that the flood plain has been formed by the lateral migration of meanders. This topography also reveals no obvious change in meander geometry, which would be indicative of a significant alteration in the discharge and/or sediment supply regimes. Sequential aerial photographs and the comparison of mid-19th and late-20th century maps reveal no significant lateral channel migration along the river (Brooks, 2002).

Radiocarbon dates from nine boreholes provide chronological control on the floodplain deposits (Brooks, 2003b). Dates ranging 940 to 7290 cal years B.P. suggest that the deposits within the specified boreholes aggraded immediately adjacent to the channel. Seen in (Figure 2), the age of the deposits and the locations of the boreholes allow past positions of the river channel to be determined from the past 8000 years.



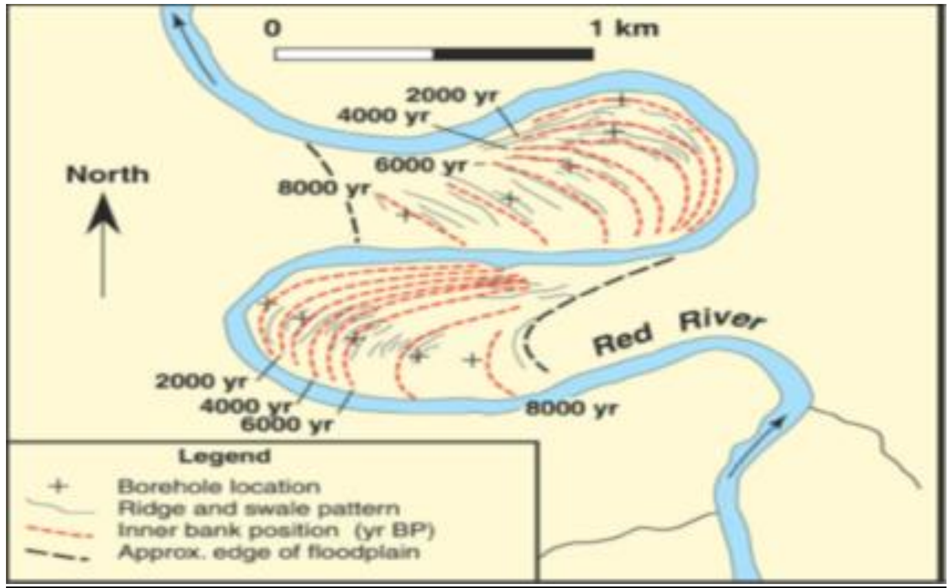


Figure 2. Map showing lateral migration meander growth at the St. Jean Baptiste study area over the past 8000 years (Brooks, 2003b). The positions of the 1000-year isochrones have been extrapolated from the age of the lateral accretion deposits at the boreholes and placed using a pattern across the floodplain.

The average rates of channel migration along the upstream meander were initially 0.35 meters/ year between 7900 and 7400 cal years B.P, then decreased to 0.18 meters/ year between 7400 and 6200 cal years B.P. and have since varied between 0.04 and 0.08 meters/ year. Throughout this study area the upstream meander has been migrating laterally at 0.04 meters/ year after 900 cal years B.P., thus implying that the river is presently undergoing long-term lateral migration at a low rate (Brooks, 2003b). Despite there being insignificant change in the channel position between mid-19th and late-20th century maps and aerial photographs, this research has revealed that the Red River channel has experienced low rates of lateral channel migration and incision over the period of the rivers' course. Refer to Appendix (A) Table (1) for average rates of lateral channel migration between transect broeholes throughout the St. Jean Baptist study area.

3.2 Satellite aerial imagery

Recent advances in technology provide another route for analysis of these channels. Remote sensing (RS) and Geographic Information Systems (GIS) have made it possible to make increasingly accurate photogrammetric measurements and analyses of the fluvial environment. The increased availability of data sources such as aerial photography and satellite imagery have made it possible to assess a much larger area more efficiently. There is a growing number of available literature on remote sensing and GIS research, but very little have dealt with the use of RS and GIS for river systems research (Martin, 2005).

Channel Migration Zone Mapping (CMZ) is based on the notion that rivers are dynamic and move laterally across their floodplains over time. The fundamental concept of CMZ mapping is to identify the corridor area that stream channel or series of stream channels can be expected to occupy over a given timeframe (Martin, 2005). The Historic Migration Zone (HMZ) is based on a composite area defined by the channel locations in a specific time period. Previous studies on rivers' similar to the Red River use these techniques over a specified timeframe to illustrate channel pattern movement, as seen in (Figure 3). Research tactics similar to these were used in calculating the rivers lateral migration rate across the Red River Valley within the vicinity of Grand Forks, ND (Method 5.2).

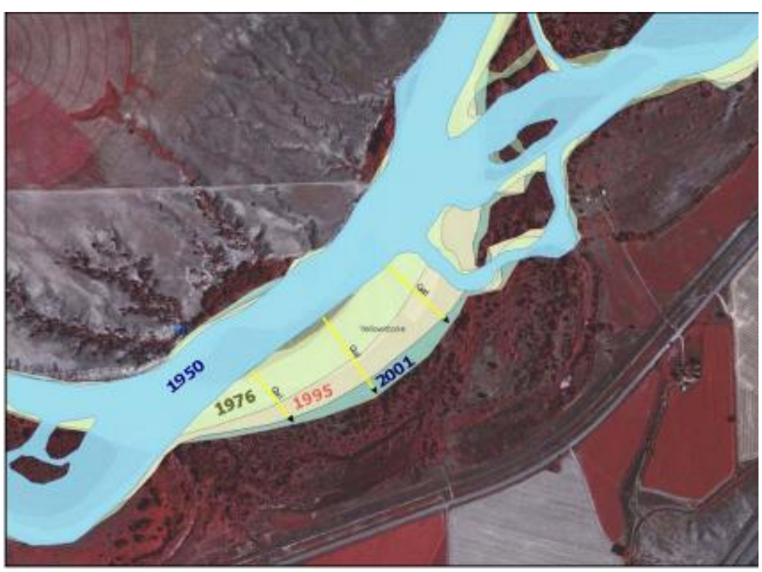


Figure 3. Composite Historic Migration Zone (HMZ) showing lateral migration from 1950- 2001; migration lines are shown as arrows.

4. Field Area

With an area of 45,000 square miles and a length of 545 river miles, the Red River of the Norths' highly sinuous, low gradient river channel stretches from Wahpeton, North Dakota to Lake Winnipeg, Manitoba and marks the North Dakota – Minnesota border (Red River Basin, 2000). The primary area of interest lies 30 river miles north and South of Grand Forks, ND and spans approximately 60 river miles in length, as seen in (Figure 4). The field area begins east of Reynolds, ND, just north of County Road 25 (47°41'56.94" N), (96°54'37.79" W) and stretches up to just north of Oslo, ND (48°12'54.45" N), (97°08'22.69" W).

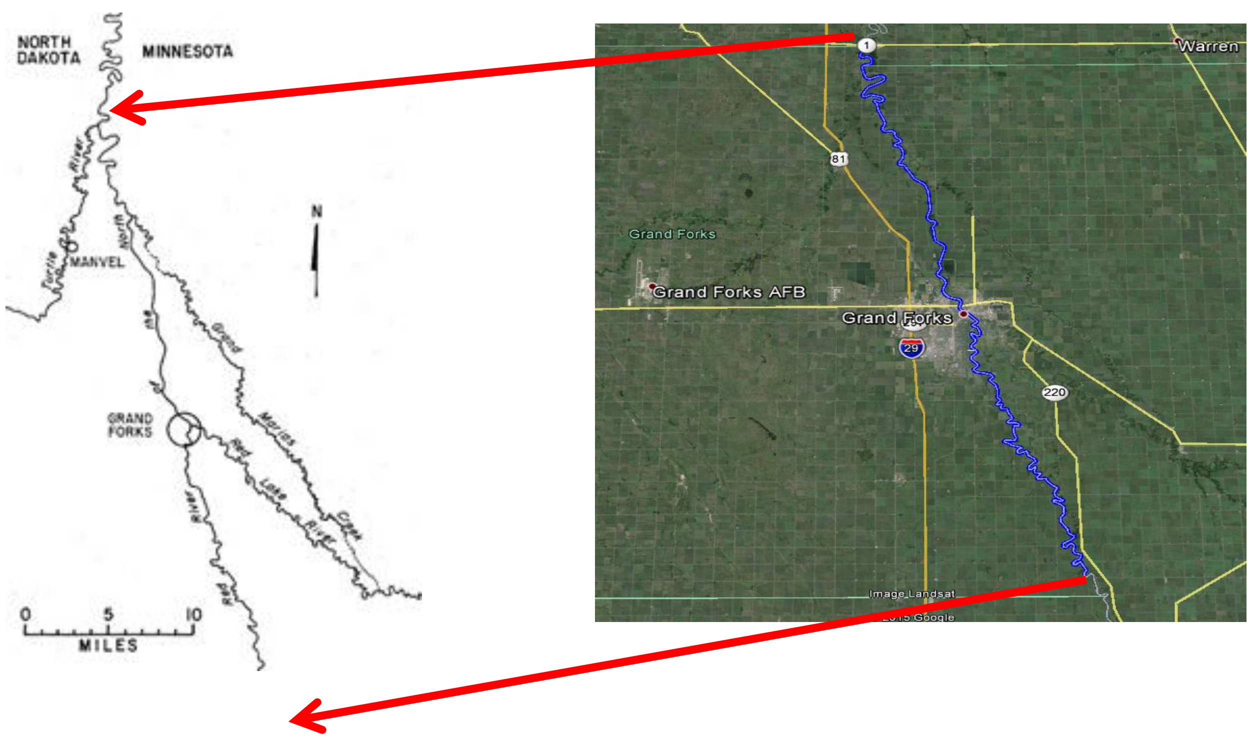


Figure 4. Using Earth Explorer, a digitized line of the River's current course marks the general study area for this research.

The Red River is one of the few rivers in the United States and Canada to flow directly north. This is due to the flatness of the basin, and the low gradient river channel. The stream gradient of the main stem of the Red River becomes much less gradual, as the river only drops about 71.02 meters over the 877.10 river kilometers between Wahpeton, ND to Lake Winnipeg, Manitoba.

As seen in (Figure 5) the slope of the Red Rivers main stem ranges from 6.86 m/km at Wahpeton-Breckenridge, to 1.06 m/km at the international boundary. From Emerson to St. Agathe the slope is 1.06 m/km, and from St. Agathe to the mouth it is 2.01 m/km. Basic trends show a decrease in gradient as you move north. The meanders are mature and the stream bed is mostly comprised of clay and silt-size materials. The principal tributaries to the Red River have similar stream-slope characteristics. Stream gradients are about 10.56 to 26.40 m/km in the upland areas, and decrease to about 5.28 to 8.45 m/km within the Red River Valley Lake Plain (Red River Basin, 2000).

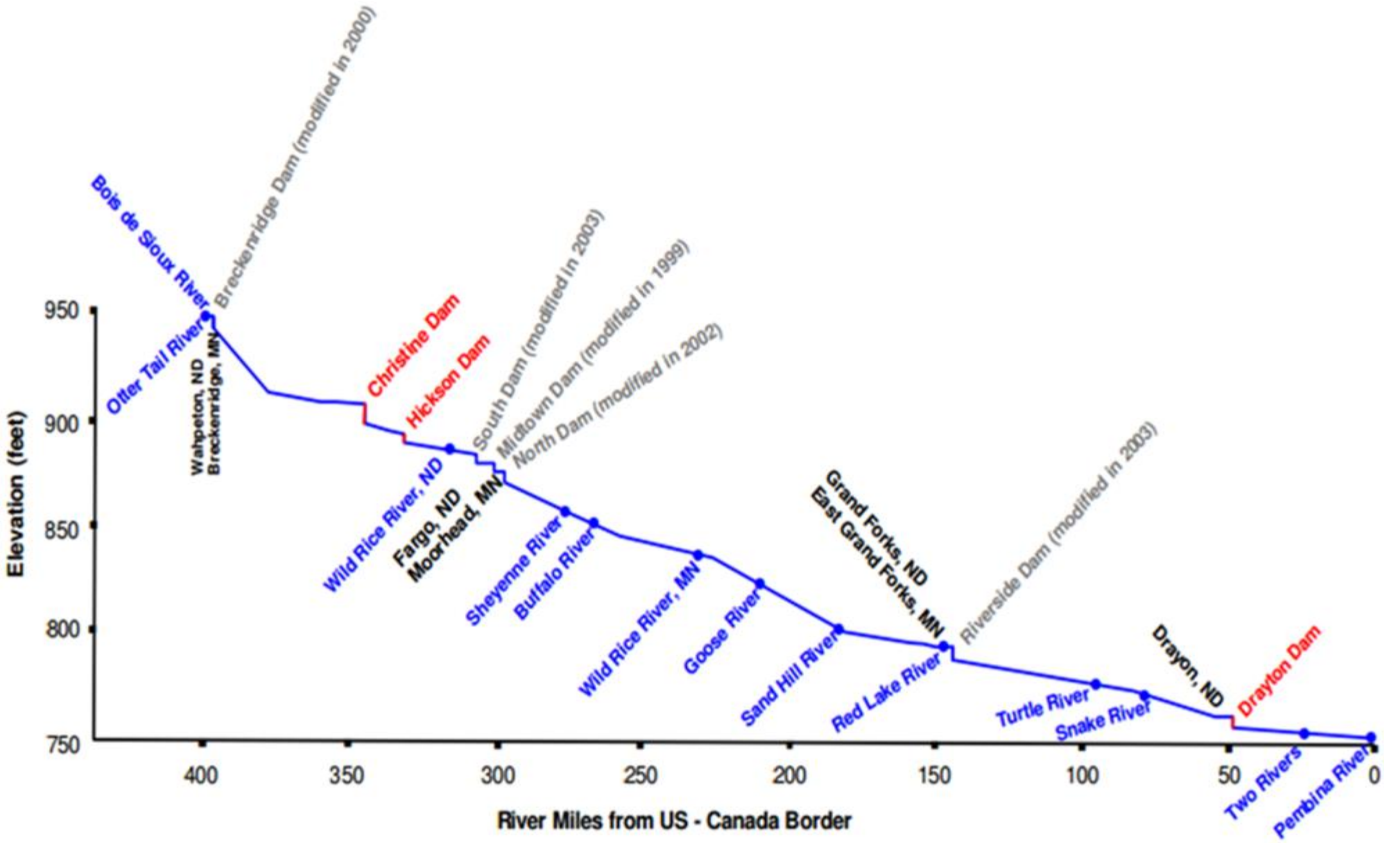


Figure 5. Longitudinal profile of the U.S. portion of Red River of the North with major cities, tributary confluences and dam locations (Department of Natural Resources, 2012).

Examination of this data suggests that there are sections within the study area that have distinct gradients. Taking a closer look, a number of knick points occur throughout the study region, showing evidence of generous elevation changes in portions of the river. Because channel slope influences stream power, changes in slope values along the study reach may translate into changes in lateral channel migration rates (Giardino 2011).

5. Methods

With this research a series of methods are utilized to further determine the rates at which this river has laterally migrated. Data for this study was obtained by the use of three separate methods which are first analyzed and then compared to the research method in section (3.1). A direct comparison of similar, unconsolidated, sinuous rivers can be further studied. Through the use of historical aerial photographs, satellite/ grey scale imagery, topographic maps, and PLAT Maps/ surveyor notes, data can be integrated into a GIS program as well as further looked in the field to be measured and analyzed. Two types of methods were used throughout this research; the first allows for a distance and time to be established, while the second allows for only a distance.

5.1 Cross Section Elevation Based Models

Using cross section, elevation based models allows for the use of remote sensing color terrain Lidar imagery to locate current and past oxbows and meander scars throughout the Red River Valley. Multiple cross sectional models are produced within the defined study area using MNTOPO viewer and Google Earth, allowing for a cross section to be taken perpendicular to the river as seen in images (A) and (B) of (Figure 6).

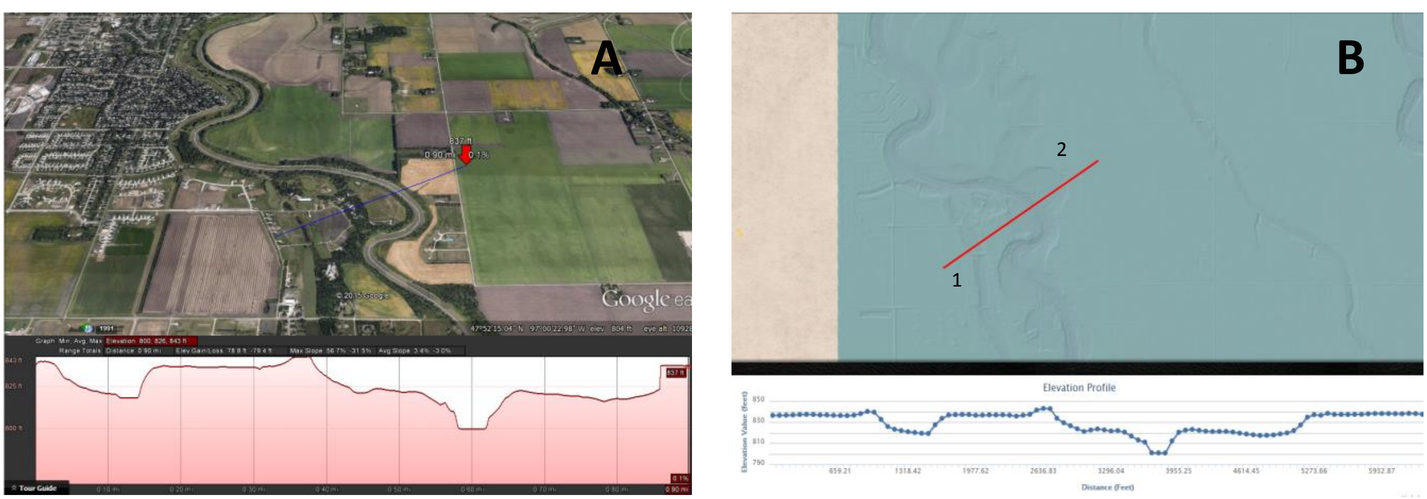


Figure 6. Images (A) and (B) depict a small section within the study area approximately 6 miles south of Grand Forks. Within image (B) channel avulsion (1) and a meander scar (2) can be seen. Image (B) shows advantage of using grey scale imagery over satellite imagery.

This method was chosen because it offers a maximum distance of the river's extent. This allows for a distance to be taken showing how far the river has laterally moved at a maximum width, within that section of the river. 13 localities were chosen as these were the only places where movement could be seen and documented using satellite and grey scale imagery. Even though a time is not established with this method, a maximum limit of 9,300 years can be used as this is the estimated date upon the final drainage of glacial Lake Agassiz, which formed what we know as the Red River of the North today.

When using this method to determine the maximum extent of the river, a few factors have to be looked at: (1) Determining whether or not the meander scar is indeed a scar or avulsion due to over flooding or excess water. (2) Are the oxbows that are present, remnants of the pre- existing channel or rather smaller ongoing or abandoned tributaries that flowed into the Red? (Figure 6) is a graphical representation of the grey scale imagery matched up with a Landsat aerial image. It shows the advantages of using grey scale imagery to locate meander scars within the Red River Valley.

5.2 Repeat Photography within ArcGIS program

The second of the three methods allows for geospatial data to be viewed, edited, and analyzed when comparing historical maps and photographs through the use of repeat photography. This is a well-established method that has become quite useful in science, as a qualitative way to document changes in an environment using a series of photographs from different time periods. This present method of study allows multiple images including black and white and false color images to analyze a channels movement from the same vantage points within different time periods.

This research allows for the designing of a map that depicts a series of time sequenced historic photographs to interpret change over time. This is done by uploading a 1962 mosaic image with a present day 2015 image into ArcMap. These photos are overlaid using the same Geographic Coordinate System (GCS), where they are geo-referenced and digitized to compare 53 years of channel migration. A transparency is used to compare point bars and cut bank localities of both photos, where line segments can be drawn to determine distance moved in x amount of years as seen in (Figure 7). Line segment measurements are then transferred in a kml to Google Earth and overlaid on a base map to show migration distances in meters/ year within specific areas where data is available.

This method was chosen as an average mean distance can be calculated for the Eastern and Western sides along the river. With a distance and a time, a rate is determined in meters/ year. With this method, only the areas from both photographs with a definite visible cut- bank or point bar can be measured.

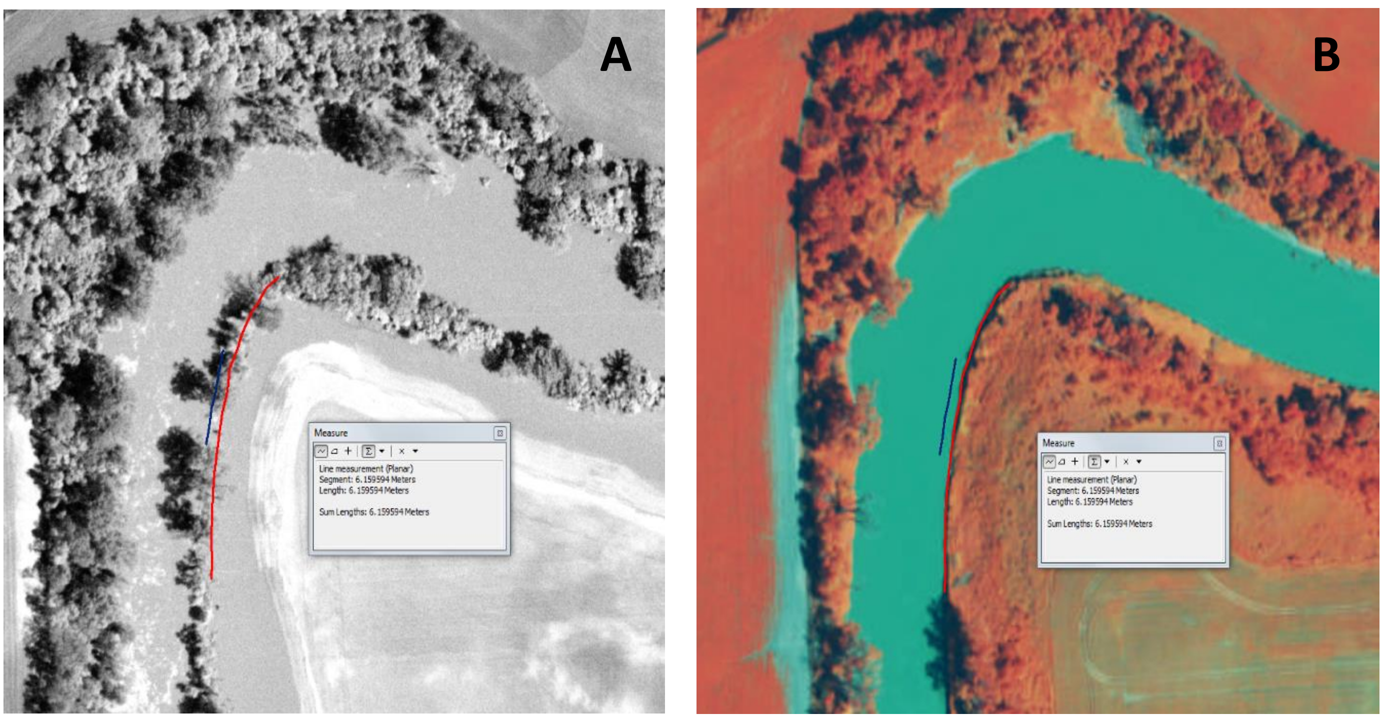


Figure 7. Image (A) represents photograph from 1962 with a digitized portion. Image (B) is a NAIP imagery photograph from 2015. A distance in point bar locations between 1962 and 2015 can be seen.

5.3 PLAT maps

This method is generally used by surveyors for property surveys and identifying parcels of land and property lines. But for this particular research GLO PLATS from 1873 were obtained through the Bismarck State Water Commission to document changes from previous measurements to present day measurements of the river. These PLATS are distinguished by Township and Range. Referring to (Appendix B) will allow a closer look at the specific Township and Ranges, as well as the descriptive localities of each measurement. For this research the field areas focus was within Townships 149, 150, 151, 152, 153, and 154 and Ranges of 49, 50, and 51. Each Township and Range PLAT is divided by section lines. Each section line is a measurable 1 mile or 80 chain lengths (5280 ft. / 1609.34 meters). Interpreting these maps requires the basic knowledge of section lines, chain lengths, placement of surveyor pins, fractional sections, as well as government lots. Research using this method required a Brunton Compass for navigating straight East (90 degrees), surveyor stake for marking each measurement, and a 200ft. measuring tape.

Figure 8. Image (A) depicts an 1873 PLAT map with length to river measured in chain lengths. Image (B) is showing the same location present day measurement. A rate of m/yr. is calculated for the 142 year difference.

Through the use of historic PLATS from 1873, specific segments can be re- measured from the surveyors' original length and documented with a rate. A previous distance measured in 1873 with measurements along the same routes today allow a rate to be calculated in meters/ year over a span of 142 years, as seen in (Appendix B).

6. Results

6.1 Interpretation of Pre-existing meander scars and oxbows

Cross sectional data from both Google Earth and MNTOPO Viewer allowed for a maximum width of the rivers' course to be calculated along 13 areas within the study area and can be seen in (Figure 9). Each locality is chosen as they are specific areas along the study area that can be identified as either oxbows from the pre-existing channel or meander scars from the rivers' previous path.

Taking a look at Table (1) of Appendix (B), measured localities south of Grand Forks range from 165.20 meters to 688.85 meters, whereas north of Grand Forks measures 774.80 meters to 1455.42 meters. As can be seen in (Figure 9), cross sections 9-13 occur south of Grand Forks, and cross sections 1-8 occur north of Grand Forks. Results for this method show that over the time span of this river, approximately 9300 years B.P., this river has moved a maximum distance of 1455.42 meters in the area. A greater distance can be seen in locations north of Grand Forks when compared to areas south of Grand Forks, thus showing an overall greater change in measurements north of Grand Forks (Figure 10). The long term minimum limiting rate for this method over for the past 9,300 years shows the river has migrated at a minimum of .08 meters/ year.

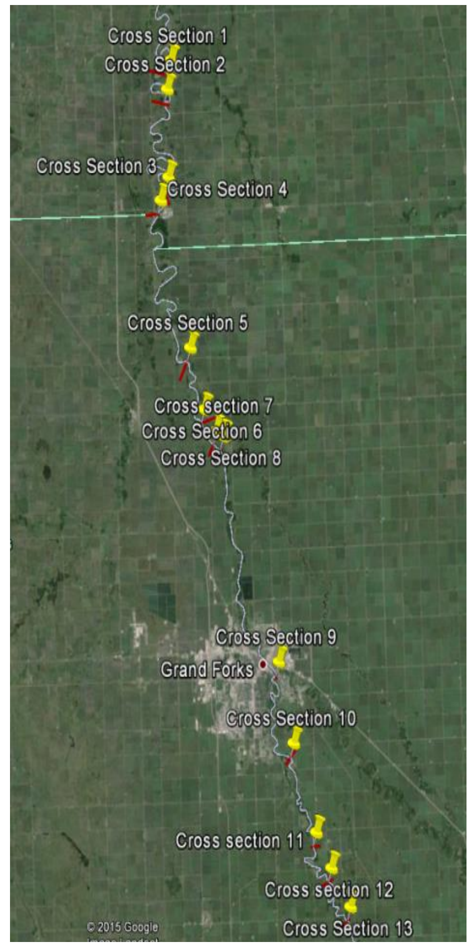


Figure 9. Locations of 13 study areas where cross sectional measurements were taken along the Red River of the

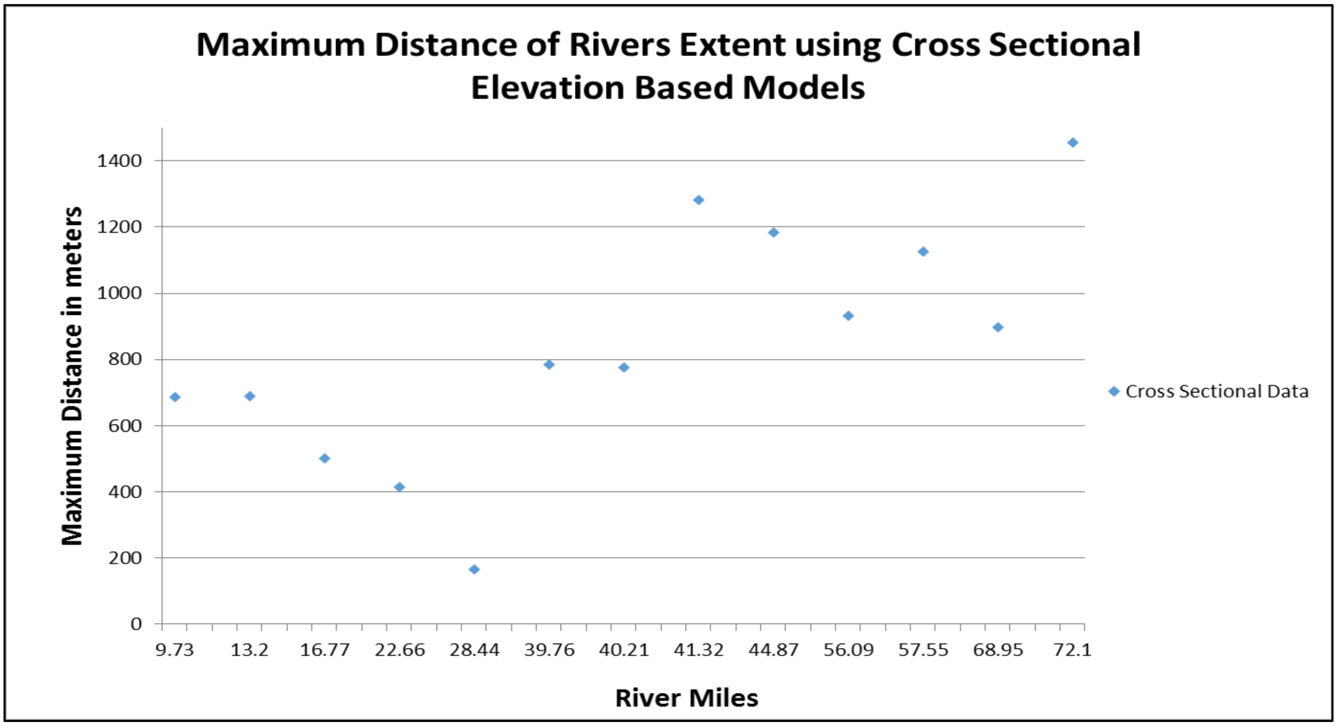


Figure 10. Image created in an Excel spreadsheet portraying a maximum distance at which a known distance of where the river has once been. Values show the maximum extent is occurring in areas north of Grand Forks, when comparing to measurements taken south of Grand Forks.

6.2 Evolution of the Channel Bar

Rectified aerial photographs and satellite imagery overlain in ArcMap software provide evidence that the Red River of the North channel, within the vicinity of Grand Forks, is very dynamic. Using this method, only 8 measurements were obtained as very few places were suitable for precise and accurate measurements along the river due to the vegetation and water levels in specific areas. Very careful placements of these measurements were taken as the water level is higher in the 1962 photo. Migration of this highly sinuous river can be seen in photos (Appendix C), proving that even with higher water levels during the time of the 1962 photo, documentation of the river migrating can still be seen in the most recent 2015 image.

A series of graphs can be seen in (Figures 11 and 12), showing the maximum distance of lateral channel migration of 53 years, as well as an average rate in meters/ year over the 53 year period. Measurements 1-8 can be seen starting south of Grand Forks and ending north of Grand Forks, as shown in Figure (1) Appendix (A). When viewing these results from Table (1) Appendix (C), as the measurements move northward along the study area, the maximum distance becomes larger. The maximum distance at which lateral migration can be documented using this method was 18.34 meters over a span of 53 years (Figure 12). The average rates for this method varied between .10 to .35 meters/ year, as can be seen in (Figure 11). Keep in mind, this shows generally low rates of channel migration when compared to similar low gradient sinuous rivers.

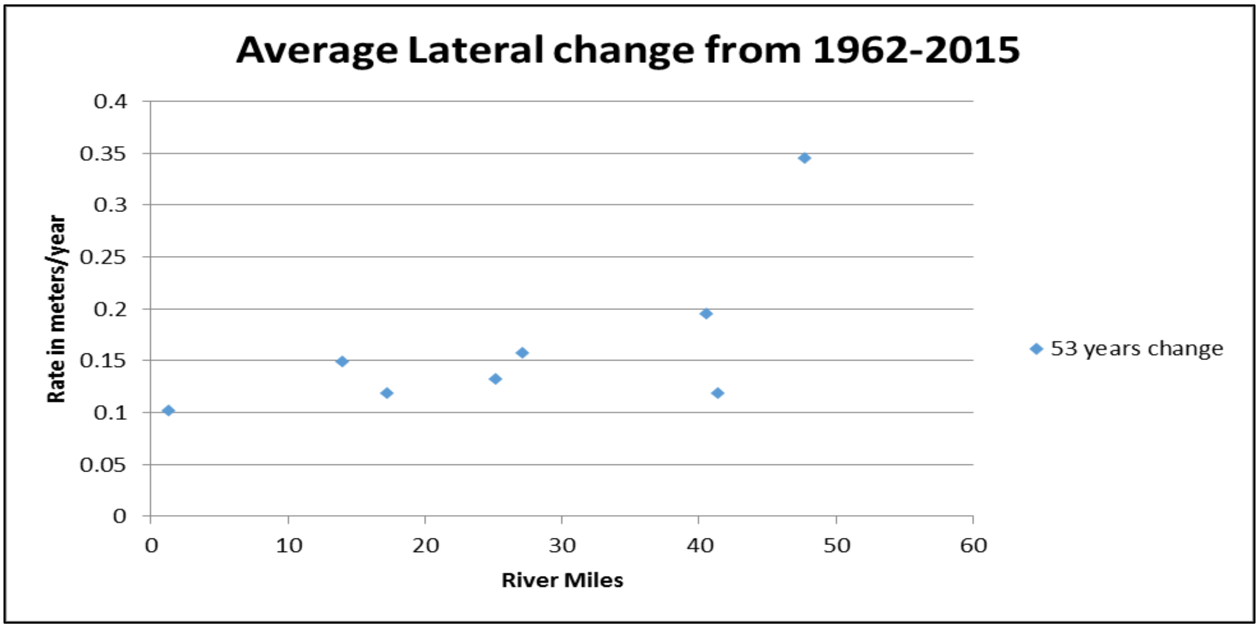


Figure 11. Image showing average lateral channel migration over a period of 53 years using overlay imagery in ArcMap.

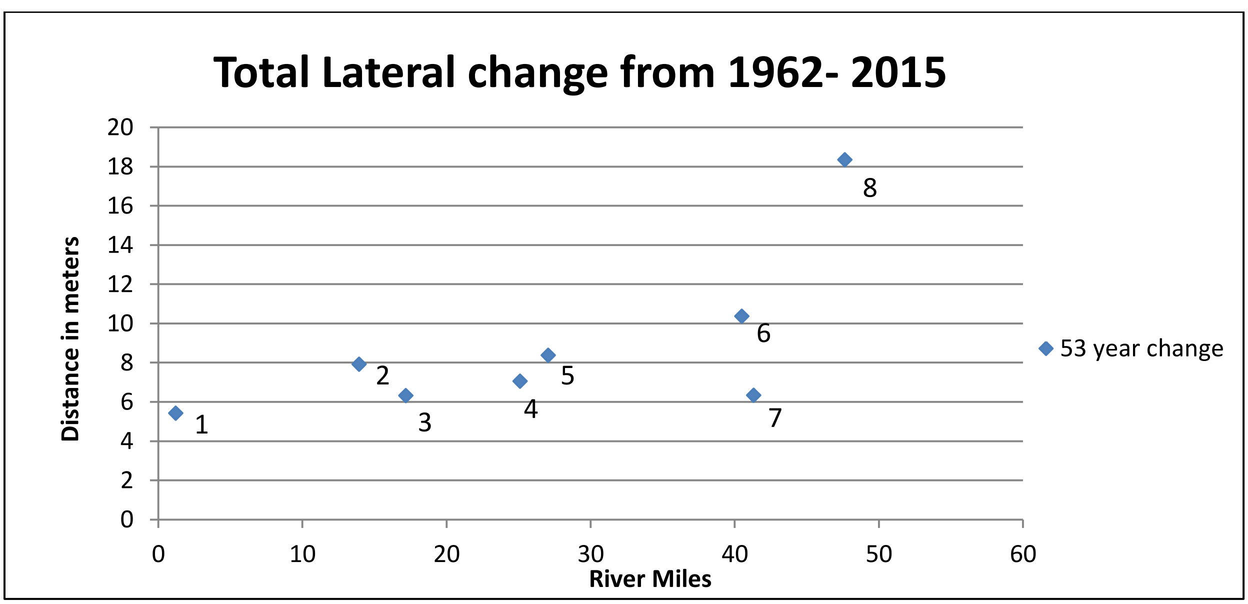


Figure 12. Image showing the total lateral channel migration rate over a period of 53 years using overlay imagery in ArcMap of 8 locations.

6.3 PLAT reflections and interpretations

Through the use of PLAT measurements dating back to 1873, a series of measurements were re- taken and documented along areas where data was most easily accessible along the river. This method allowed for 10 localities to be looked at over a span of 142 years. Each location was chosen where PLAT measurements were available during that time, and could be re- measured for a new length to the river.

Looking at (Figures 13 and 14), over the 9,300 years B.P, this method shows that specific areas have moved a maximum distance of 54.4 meters over the course of 142 years' time, averaging out to be 0.38 meters/ year. Results for this method show an influx, ranging anywhere from 0.01 to 0.38 meters/ year over the span of 142 years as documented in Table (1) of Appendix (D). Rates for this method show no general trend in (Figure 13), but very similar rates to that of the repeat photography method can be seen. The measurement tallied in orange was taken from a PLAT map more recent, dating back to 1956. For this particular set of results obtained using method 5.3, distances will vary depending upon the quality of each measurement taken by the original surveyor, as well as the quality of the most recent measurement. It will also depend upon the error obtained in their results.

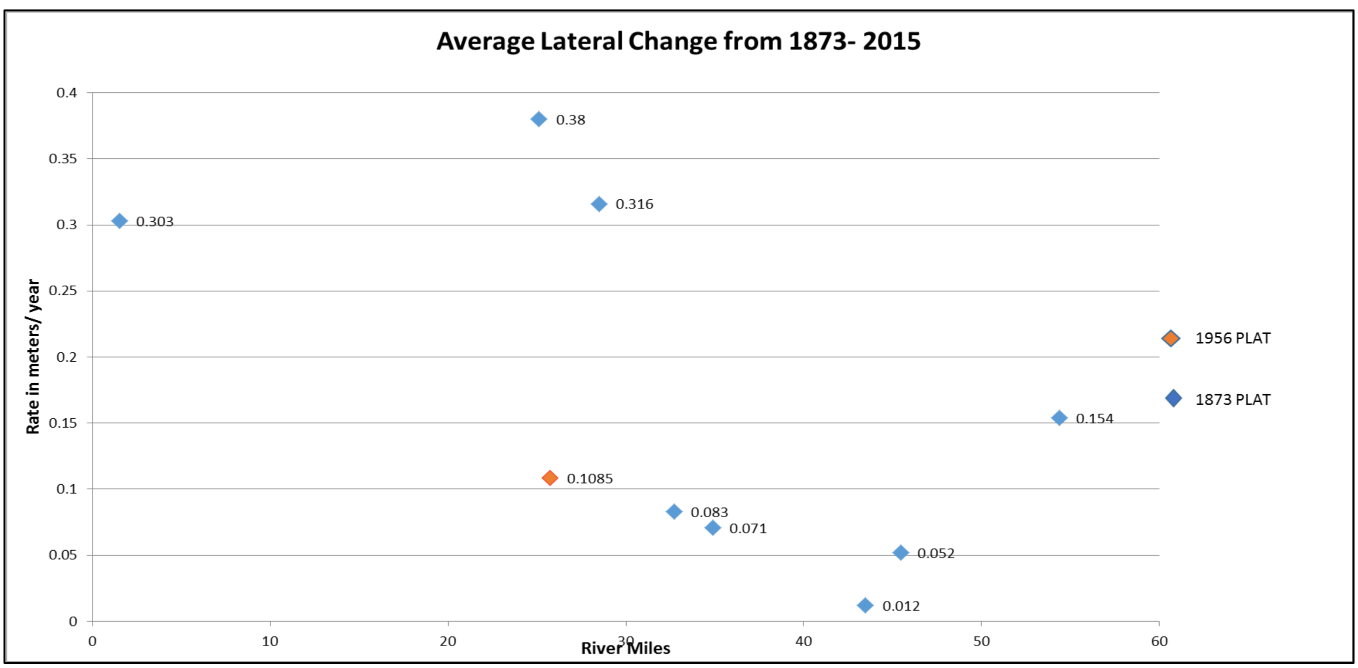


Figure 13. Graph showing the average lateral migration rates of 9 locations from a single location PLAT map in 1956 and the rest in 1873. Distances were measured recently and recorded as so.

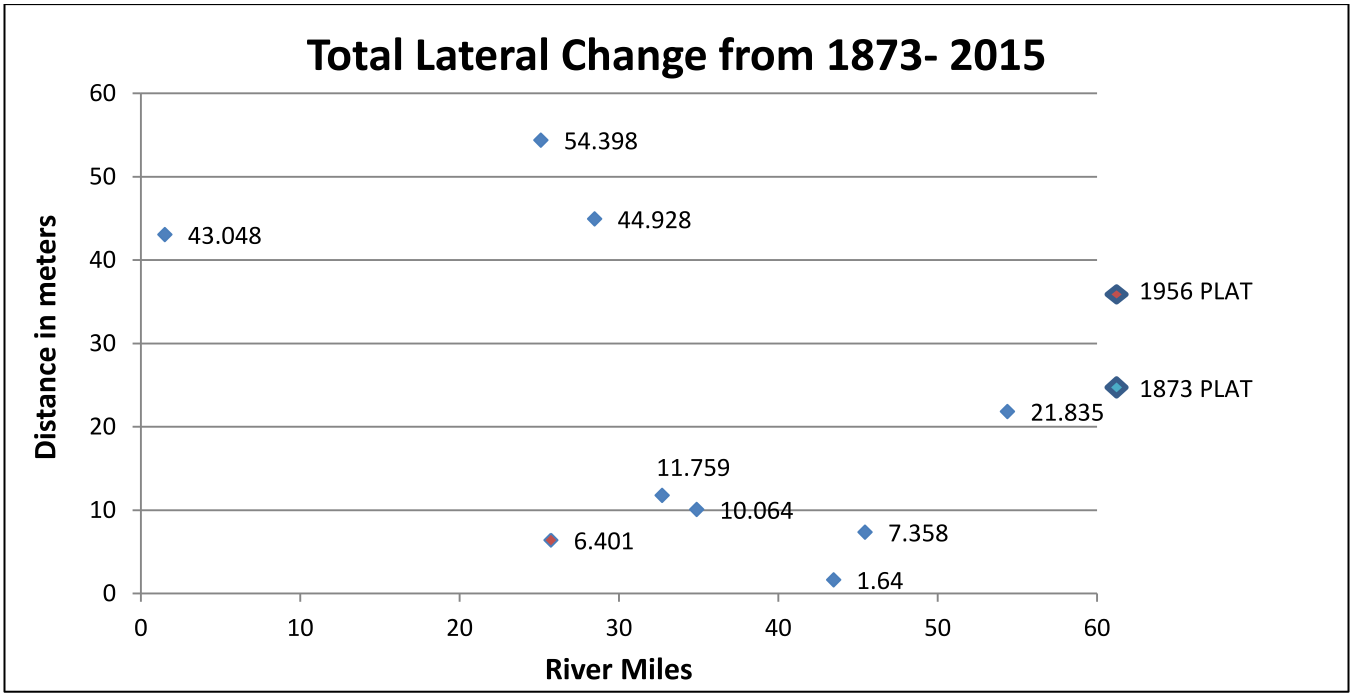


Figure 14. Graph showing the total lateral migration rate of 9 locations from a single location PLAT map in 1956 and the rest in 1873. Distances were measured recently and recorded as so.

Each measurement from the three methods used is documented and recorded, and can be seen overlain on a Google Earth photo in Appendix (A) Figure (1). All cross sectional measurements (5.1 & 6.1) are marked with a yellow pin labeled south to north, Cross Section 13 – Cross Section 1. All measurements taken with repeat photography within the ArcMap program (5.2 & 6.2) can be seen by green pins labeled 1-8 south to north. The last of the three sets of measurements taken include a series of PLATs (5.3 & 6.3) that can be seen by red pin drops and follow no precise order as they were taken at easiest convenience.

These results not only tell us events or rates from the past, but also what to expect in the future. With an average rate calculated over the past 142 years, a representation can be created of what is to be expected in the future 25, 50, and 100 years, given it continues acting at a constant rate. With this in mind, the maximum rate of lateral channel migration within the study area is 0.38 meters/ year, and an average rate of 0.16 meters/ year. Looking at (Figure 15), the table represents the maximum and average rates of lateral channel migration at 25, 50, and 100 years from now.

Number of years	Max Rate (meters)	Average Rate (meters)
	0.38	0.165
25	9.5	4.13
50	19	8.25
100	38	16.5

Figure 15. Table of the maximum and average rate values calculated from known measurements from the past for 25, 50, and 100 years to come.

7. Discussion

Analysis of the cross section elevation based models, aerial photographs, and historic plat maps reveal a complex history of the Red River Channel near Grand Forks, ND. The Red River of the North is an open ecosystem that is in constant interaction with its banks, moving from source to mouth, and constantly changing. Basis for this change in the overall system is due to the gradual change of physical environmental conditions such as the width, depth, water flow characteristics such as velocity, and temperature.

Keep in mind, each of the three methods could only be used for specific portions of the river as data was limited and/ or skewed. Adequate knowledge can be taken from this study, but careful documentation and locations of measurements had to be looked at and chosen wisely for it to be successful.

The downstream, decreasing gradient helps support these results as the gradient of the Red River averages 7 cm/ km in the southern Valley (Fargo- Halstad), and drops to 2 cm/ km in the northern valley region (Drayton-Pembina). Results from (Brooks, 2002) can help conclude that migration rates are greater in the southern portion near Grand Forks, ND than in the previous research site St. Jean Baptiste. The river within (Brooks, 2002) study area is currently averaging 0.04- 0.08 meters/ year and is presently undergoing long-term lateral migration at a low rate. Rates within the study area near Grand Forks fluctuate between 0.01 and 0.38 meters/ year. The average rate for all measurements obtained throughout this study area are greater than what was seen in the St.Jean Baptiste study area.

With that in mind, the general importance of this topic concerns a great deal to the community, as it can effect the future infrastructure within the river's watershed. Knowing these rates at which this river is currently acting allows for forecasting of future rates. Looking at (Figures 15 and 16), relativley low rates of migration are occurring within this confined study area. As seen in (Figure 16), these low rates show no potential risk or harm to the city's infrastructure within the next 100 years at a maximum rate of 38 meters. This image was produced to show the significance of the migration rates over the next 100 years, showing that within Grand Forks the only potential risk may be losing part of the sidewalk.

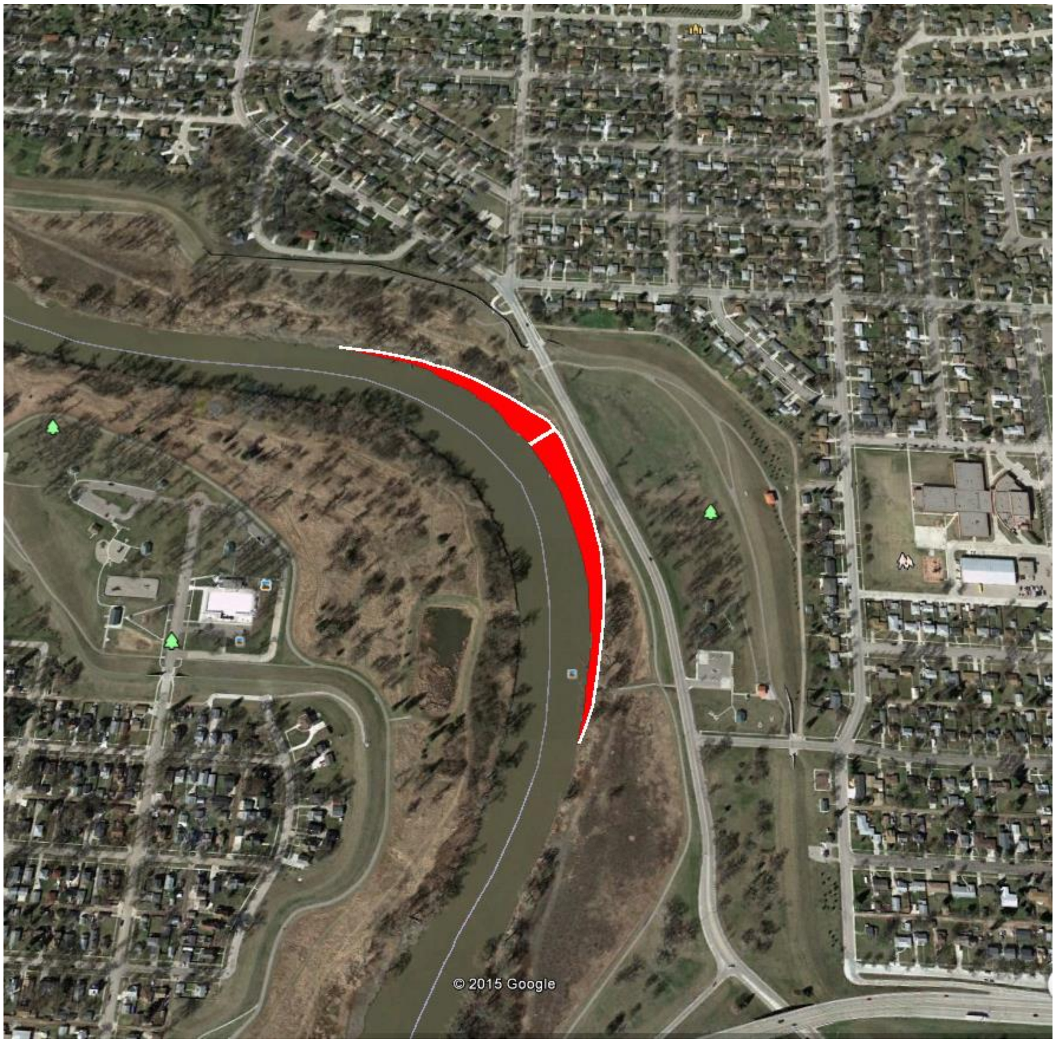


Figure 16. Photo taken from Google Earth showing an interpretation of what a specific meander may look like 100 years from now, using the maximum rate of 0.38 meters/ year or 38 meters over 100 years.

With these numbers, keep in mind the level of error that may have occurred while completing this research. A level of uncertainty occurs because no error was documented when these PLATs were taken 142 years ago. Some measurments may be skewed or could show fluctuation. But through the many measurements taken here within the study area, adequate representations were completed and represent this study area very well. Taking a look at (Figure 17), the average rate comparing all three methods can be seen. The average lateral channel migration rates appear as dots for both methods, as the long term minimum limiting rate appears as a red dotted line across the graph. With this data its conceivable to say, based off of these measurements, the actual rate could fall anywhere within the graph but above the line, as the line depicts the mere minimum. This meaning the value cant be any lower but can certainly be higher.

Additional research still needs to be done to determine further localities that can be measured in both an overlain imagery into ArcMap, as well as in PLAT measurements. The more points available will give a better understanding on the specific rates within other areas of the river. Once this area has been covered, the field area can then expand north and south to get the rates at which this is occurring along the full Red River of the North.

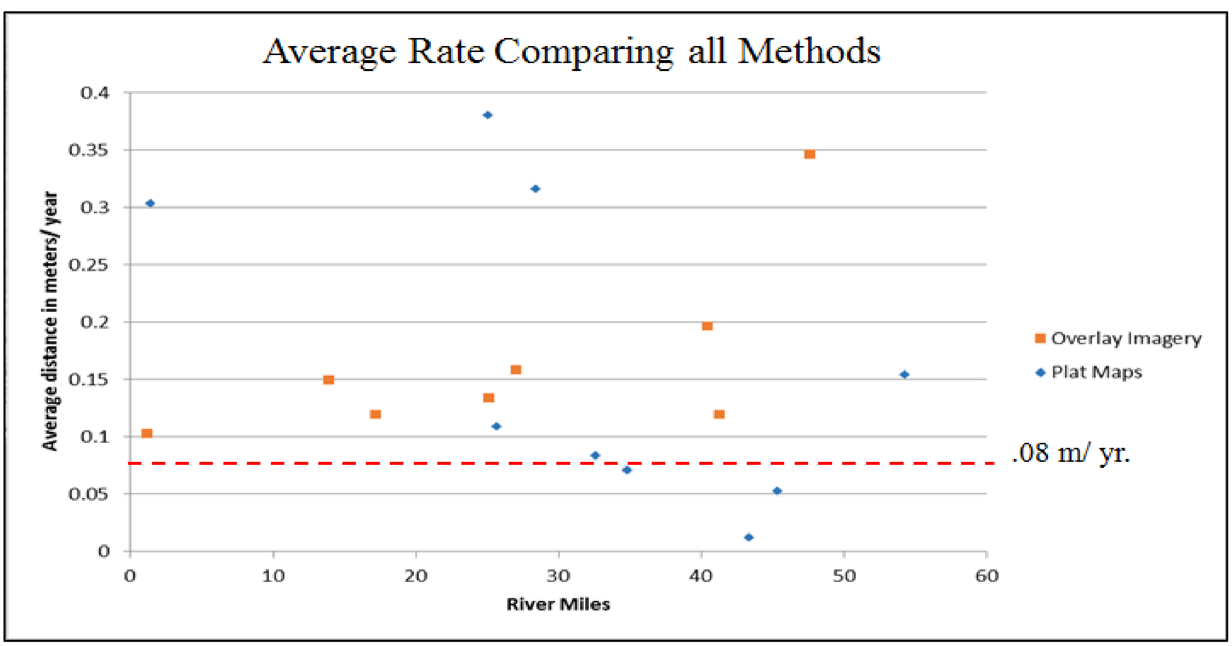


Figure 17. Graph showing the average lateral migration rate comparing all methods used for this research. The long term minimum limiting rate is shown by the red dotted line at a value of .08 meters/ year.

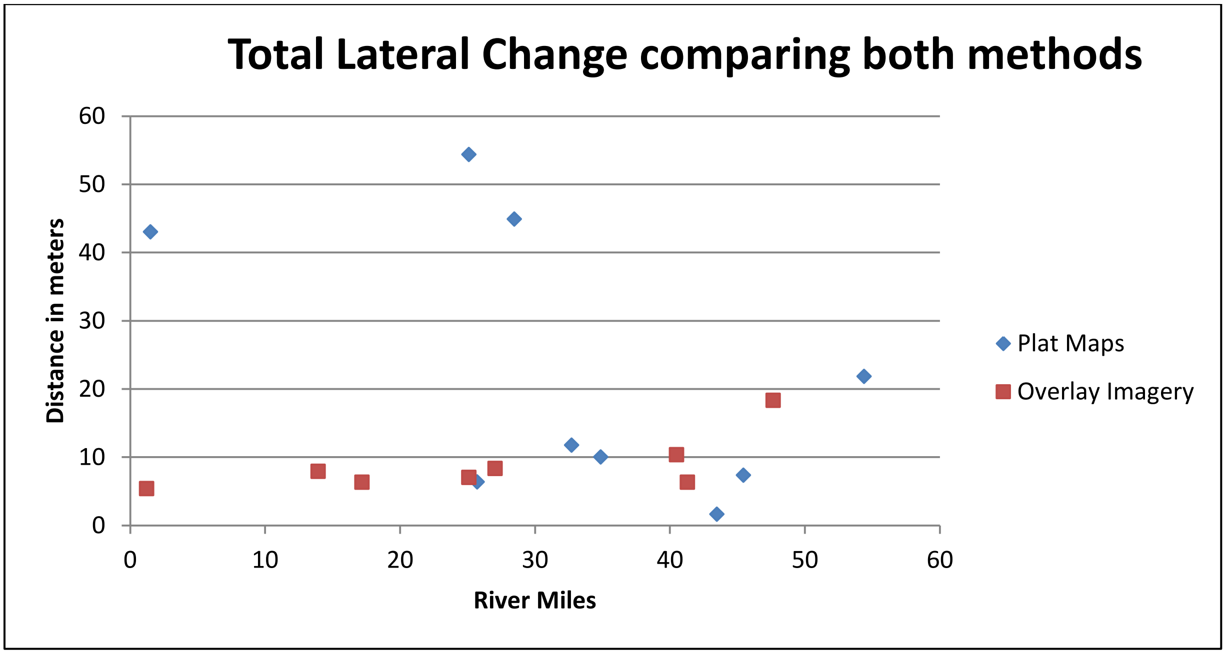


Figure 18. Graph showing the total lateral migration rates as can be seen all in positive values to depict a minimum and maximum distance along the study area of the river.

8. Conclusion

The purpose of this study was to analyze and interpret 142 year old PLAT maps and 53 year old aerial photographs to determine lateral channel migration rates of the Red River of the North. Focusing specifically on the Grand Forks area, this study aimed to highlight the advantages of applying geospatial techniques, such as remote sensing (RS) and geographic information systems (GIS), to a rivers course to determine the maximum and average distances occurring. This was done by: (1) Geo- referencing and digitizing a photo from 1962 and 2015 for interpretation, (2) using remote sensing color terrain Lidar imagery to create cross sectional profiles to determine a maximum extent, and (3) assessing PLATS from 1873 to determine previous extents of the river.

With the exception of a few points experiencing rates higher than the average rate, a common trend can be seen in (Figures 17 and 18). These rates fluctuate between 0.01 and 0.38 meters/ year within the study area, and show a maximum rate of 0.38 meters/ year. With the uncertainty of error within each of the three methods, it can be seen that all results are similar in regards to this rivers' course.

In Summary, the study area shows new results that directly relate to previous work done along the Red River of the North within St. Jean Baptiste, Manitoba. Rates within St. Jean Baptiste study area fluctuate between 0.04 and 0.08 meters/ year, whereas the study area in Grand Forks has an average rate of channel migration of 0.16 meters/ year. These migration rates that are seen in both study areas correlate with what is seen within the stream gradient profile (Figure 5). The stream- slope characteristics decrease as you move northward where it reaches 1.056 m/km at the international boundary near St. Jean Baptiste. This evidence helps support the interpretation that measurements taken within the vicinity of Grand Forks study area have greater rates of channel migration than that occurring within St. Jean Baptiste.

The long term rate is .08- .38 meters/ year over 9,300 years. This study implies that the river is currently undergoing long term lateral migration at a low rate in comparison to rivers such as that of Newtok, Alaska. Despite their being drastic changes in the channels position between the mid- 19th and 20th century maps and photographs, this study demonstrates that a low energy, mud dominated river can experience progressive yet slow lateral channel migration. Viewing these low rates over the span of the study area shows no potential risk or harm to the citys' infrastructure within the next 100 years. With these results further studies can be made that interpret other areas of this river to understand the movement and processes of this dynamic river system.

9. Acknowledgements

First and foremost, I want to thank Dr. Jaakko Putkonen for advising me throughout this project, David Bartholomew for the assistance in gathering/ interpreting Plat maps and surveyor notes, the Grand Forks City Deeds Office as well as the county Hwy Dept. for access to old river documents, Ana Crowell for the aid in GIS work, Morgen Burke for the digitized 1962 mosaic, and lastly Robert Schneider and Timmy West for assistance in the field gathering data. Comments by friends and faculty on drafts of this paper are sincerely appreciated.

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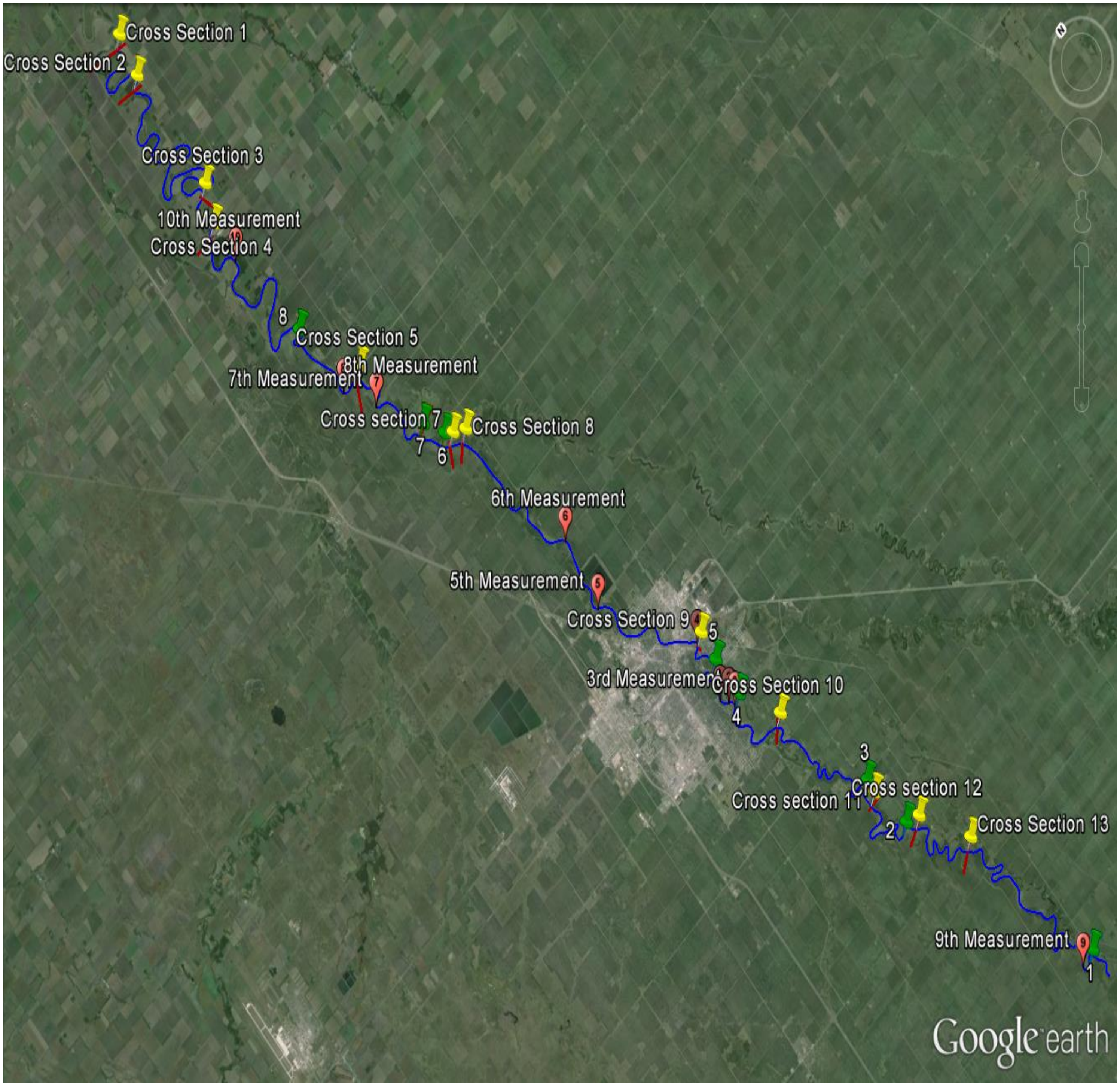
Appendix A.

Table 1.

Locations	Distance (m)	Ages of bank–borehole or borehole–borehole (cal years B.P.)[a]	Difference in averaged age (cal years B.P.)	Upper and lower difference in age range at 1σ (cal years B.P.) [a]	Average rate of channel migration (m/year)	Range of average rate of channel migration at 1σ (m/year)
Bank to 99RR1A	40	0[b]–1010	1010	930–1150	0.04	0.03–0.04
99RR1A to 99RR1B	152	1010–2290	1280	1040–1440	0.12	0.11–0.15
99RR1B to 99RR1C	208	2290–5530	3240	3070–3420	0.06	0.06–0.07
99RR1C to 99RR1E	541	5530–8090	2560	2410–2720	0.21	0.20–0.23
Bank to 99RR3A	38	0[b]–920	920	800–940	0.04	0.04–0.05
99RR3A to 99RR3B	127	920–2610	1690	1410–1930	0.08	0.07–0.09
99RR3B to 99RR3C	191	2610–6170	3560	3320–3930	0.05	0.05–0.06
99RR3C to 99RR3D	215	6170–7360	1190	1040–1380	0.18	0.16–0.21
99RR3D to 99RR3E	171	7360–7850	490	310–650	0.35	0.26–0.55

Figure 1.

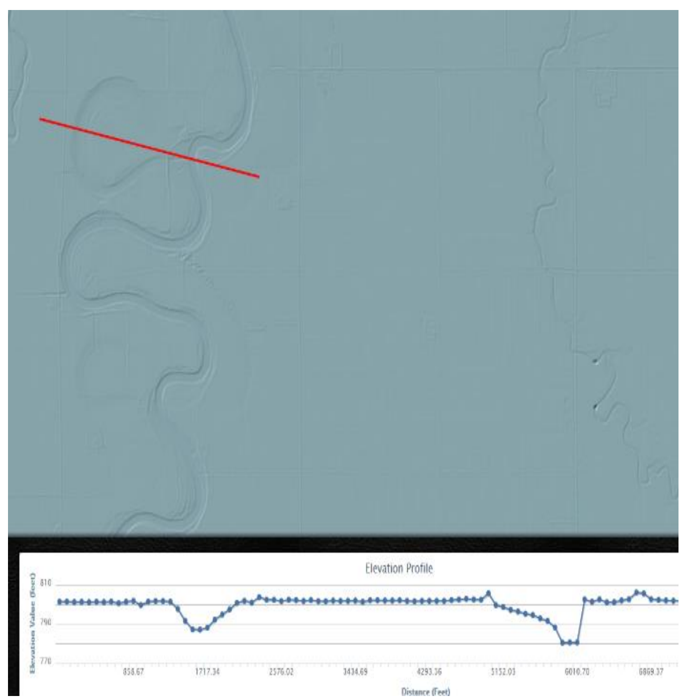

Cross Section 1
Cross Section 2
Cross Section 3
10th Measurement
Cross Section 4
8
Cross Section 5
8th Measurement
7th Measurement
Cross section 7
Cross Section 8
7
6
6th Measurement
5th Measurement
Cross Section 9
5
3rd Measurement
Cross Section 10
4
3
Cross section 12
Cross section 11
2
Cross Section 13
9th Measurement
1
Google earth

Appendix B.

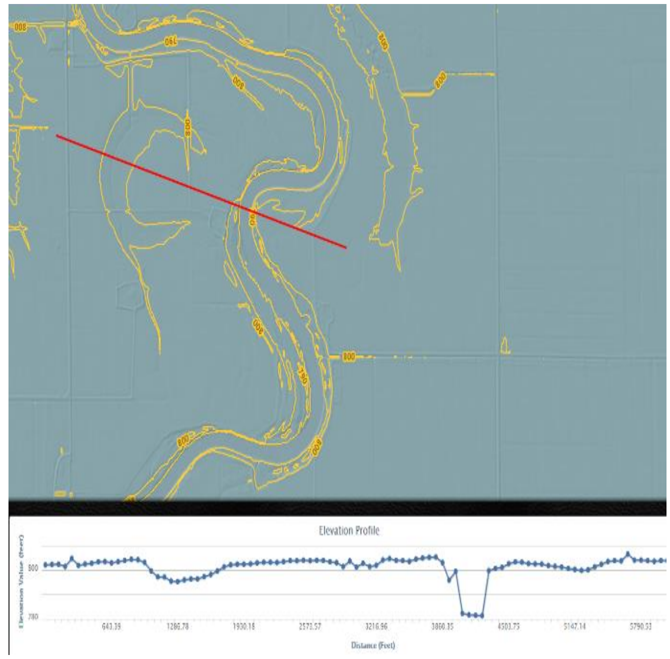
Cross Section Elevation Based Models

Table 1.

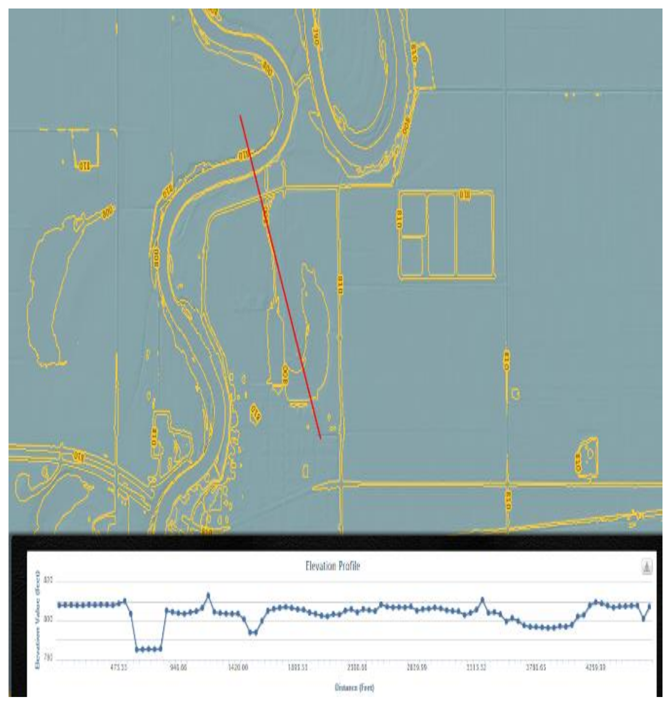
Cross section	Latitude	Longitude	Max Distance	River miles
1	48°16'33.68"N	97° 7'31.32"W	4774 ft./ 1455.42 meters	72.1
2	48°15'32.77"N	97° 7'49.63"W	2945 ft./ 897.64 meters	68.95
3	48°12'25.48"N	97° 7'53.51"W	3692 ft./ 1125.32 meters	57.55
4	48°11'36.79"N	97° 8'28.72"W	3057 ft./ 931.77 meters	56.09
5	48° 6'21.11"N	97° 6'40.76"W	3887 ft./ 1184.76 meters	44.87
6	48° 4'8.29"N	97° 5'48.56"W	4208 ft./ 1282.60 meters	41.32
7	48° 3'22.11"N	97° 5'1.43"W	2542 ft./ 774.80 meters	40.21
8	48° 3'9.59"N	97° 4'31.90"W	2570 ft./ 783.34 meters	39.76
9	47°55'5.16"N	97° 1'6.64"W	542 ft./ 165.20 meters	28.44
10	47°52'10.64"N	97° 0'13.46"W	1360 ft./ 414.53 meters	22.66
11	47°48'58.78"N	96°58'49.20"W	1643 ft./ 500.79 meters	16.77
12	47°47'41.40"N	96°57'50.37"W	2260 ft./ 688.85 meters	13.2
13	47°46'16.81"N	96°56'35.70"W	2251 ft./ 686.11 meters	9.73



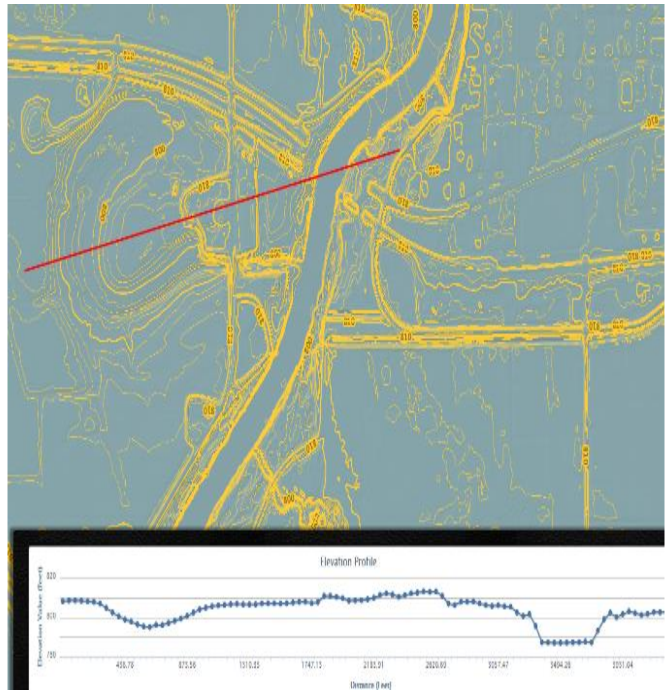

803 ft
0 ft
1.5%
Cross Section 2
© 2015 Google
Google earth
1991 Imagery Date: 9/1/2013 48°15'35.16" N 97°07'59.12" W elev 803 ft eye alt 5880 ft
Graph: Min, Avg, Max Elevation: 780, 801, 806 ft
Range Totals: Distance: 0.97 mi Elev Gain/Loss: 55.9 ft, -54.7 ft Max Slope: 44.6%, -37.8%
806 ft
803 ft
780 ft
1.5%
Tour Guide
0.25 mi
0.5 mi
0.75 mi
0.97 mi


Elevation Profile
Elevation Value (feet)
Distance (Feet)

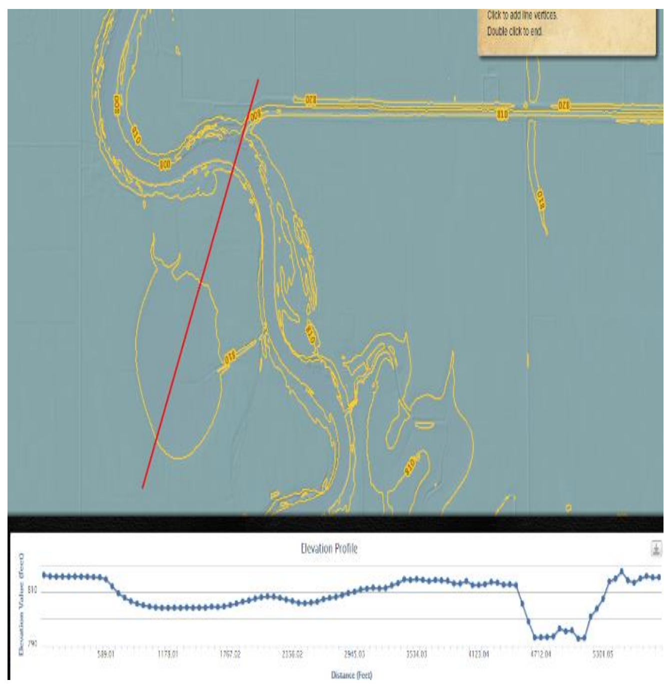

Cross Section 3
Google ear
Tour Guide


Elevation Profile
Elevation Value (feet)
Distance (Feet)

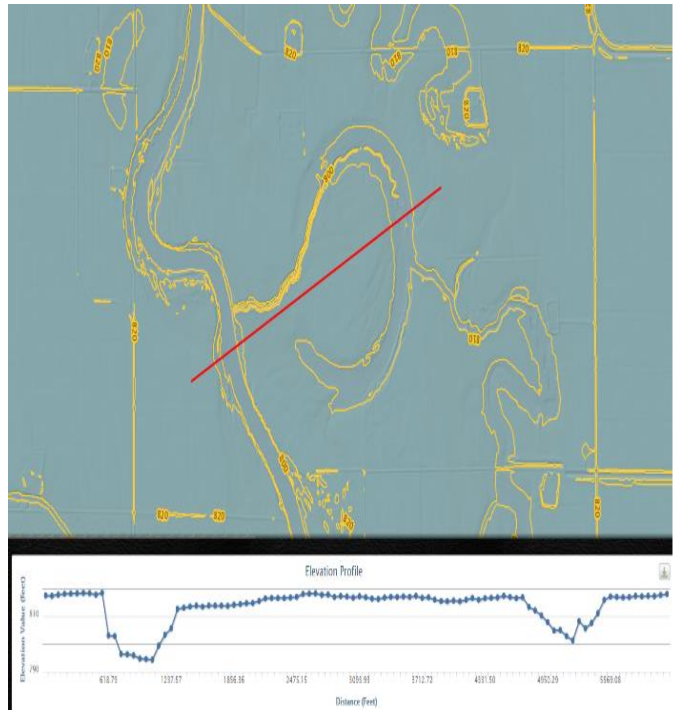

Cross Section 4
Google earth
Tour Guide

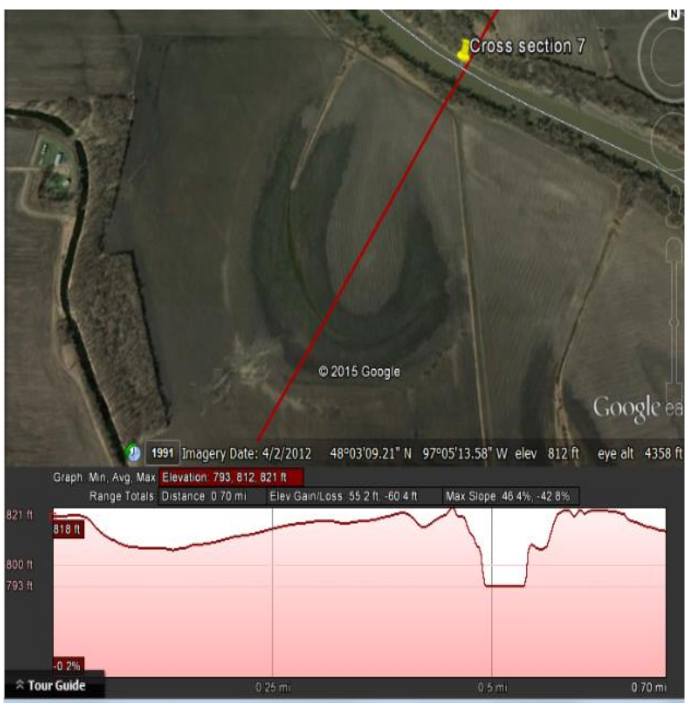

Elevation Profile

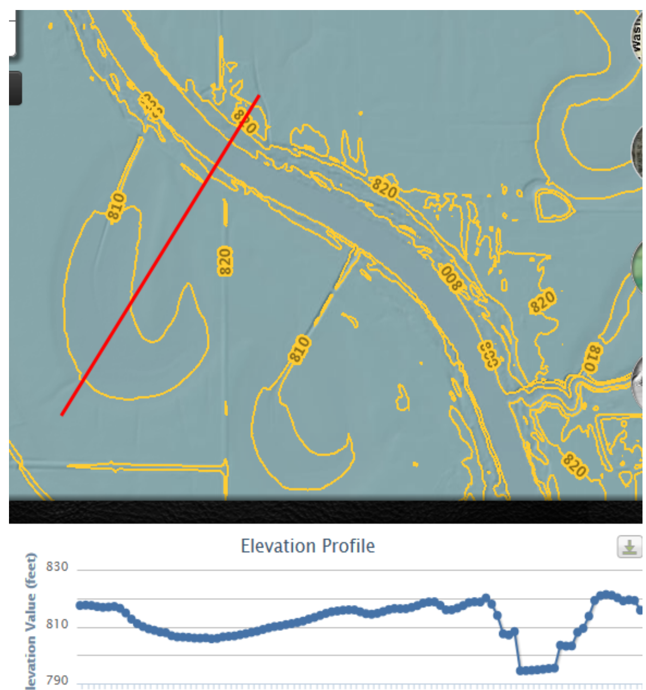

Cross Section 5
© 2015 Google
Tour Guide


Click to add line vertices.
Double click to end.
Elevation Profile
Distance (Feet)

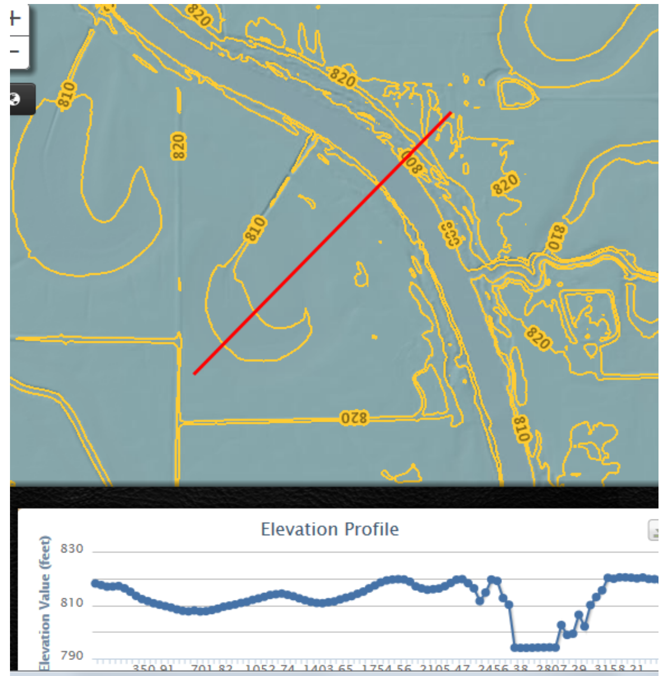

Cross Section 6
© 2015 Google
Google earth
1991 Imagery Date: 4/2/2012 48°04'14.07" N 97°05'18.46" W elev 816 ft eye alt 11967 ft
Graph: Min, Avg, Max Elevation: 792, 813, 819 ft
Range Totals: Distance: 1.05 mi Elev Gain/Loss: 74.5 ft, -74.3 ft Max Slope: 26.5%, -22.8%
819 ft
800 ft
792 ft
817 ft
1.0%
2321 ft
0.25 mi
0.5 mi
0.75 mi
1.05 mi
Tour Guide


Elevation Profile
Distance (Feet)

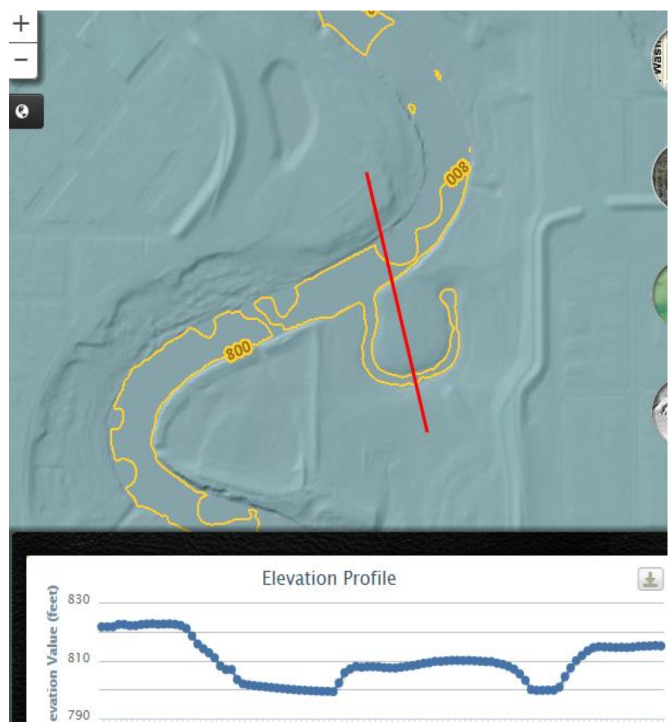

Cross section 7
© 2015 Google
1991 Imagery Date: 4/2/2012 48°03'09.21" N 97°05'13.58" W elev 812 ft eye alt 4358 ft
Graph: Min, Avg, Max Elevation: 793, 812, 821 ft
Range Totals: Distance: 0.70 mi Elev Gain/Loss: 55.2 ft, -60.4 ft Max Slope: 46.4%, -42.8%
821 ft
800 ft
793 ft
818 ft
-0.2%
0.25 mi
0.5 mi
0.70 mi
Tour Guide


810
820
800
Elevation Profile
830
810
790
Elevation Value (feet)

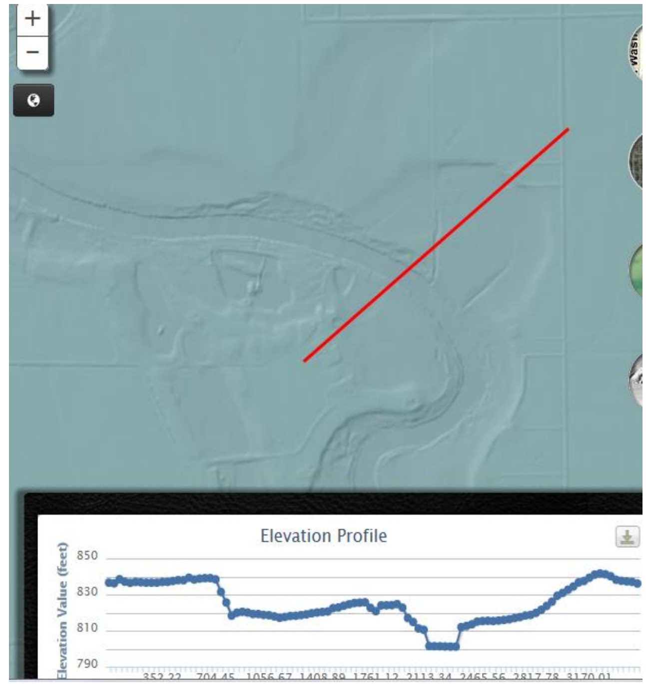

Cross Section 8
© 2015 Google
Google earth
1991 Imagery Date: 4/2/2012 48°03'05.32" N 97°04'46.26" W elev 817 ft eye alt 3962 ft
Graph: Min, Avg, Max: Elevation: 793, 812, 820 ft
Range Totals: Distance: 0.6 mi Elev Gain/Loss: 61.9 ft, -59.9 ft Max Slope: 33.6%, -55.0%
820 ft
817 ft
800 ft
793 ft
0.4%
Tour Guide
0.25 mi
0.5 mi
0.6 mi

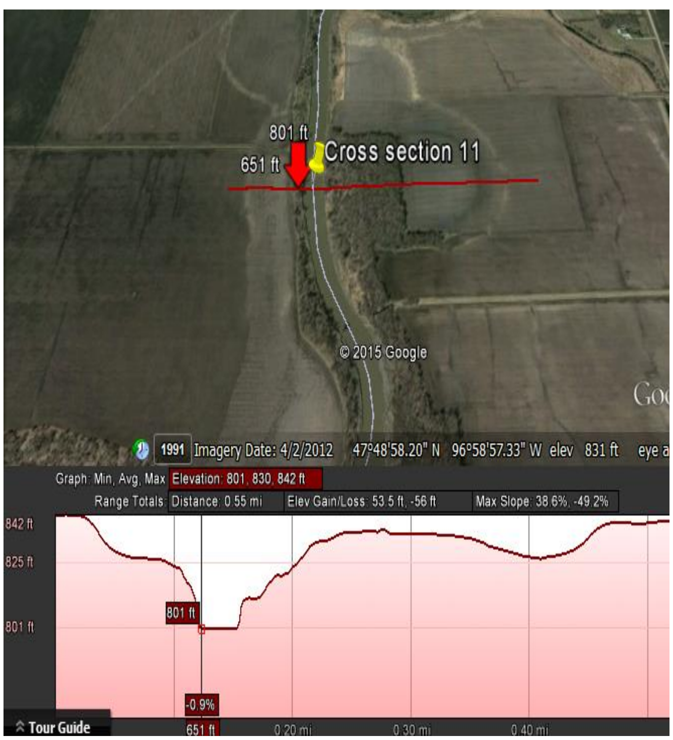

820
810
Elevation Profile
Elevation Value (feet)
830
810
790

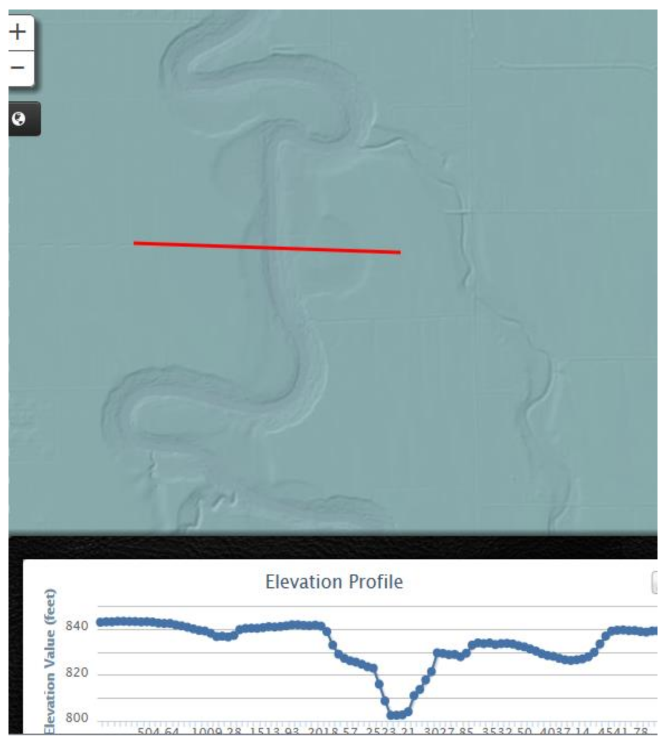

Cross Section 9
© 2015 Google
Google
1991 Imagery Date: 4/2/2012 47°55'06.71" N 97°01'29.84" W elev 833 ft eye alt 2589 ft
Graph: Min, Avg, Max: Elevation: 798, 809, 823 ft
Range Totals: Distance: 1152 ft Elev Gain/Loss: 32.9 ft, -37.7 ft Max Slope: 42.4%, -53.3%
823 ft
822 ft
798 ft
0.1%
Tour Guide
250 ft
500 ft
750 ft
1000 ft
1152 ft


800
Elevation Profile
Elevation Value (feet)
830
810
790

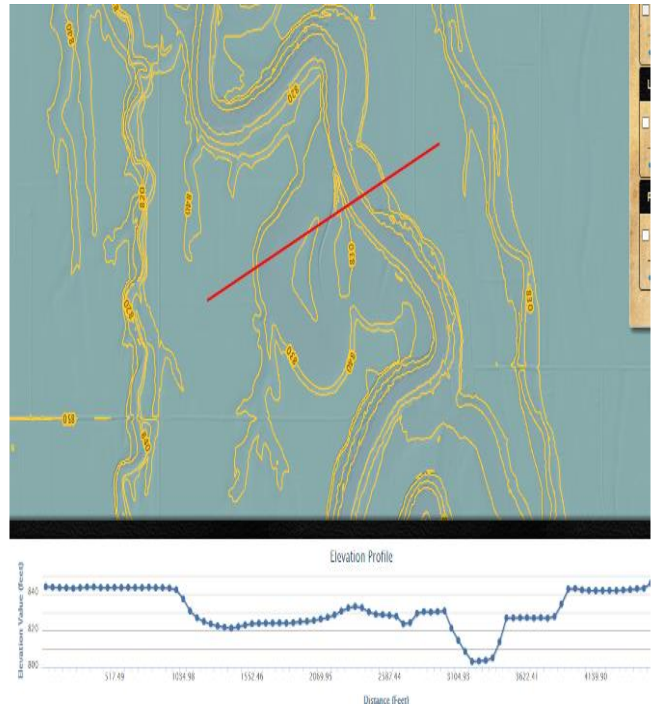

Cross Section 10
© 2015 Google
1991 Imagery Date: 4/2/2012 47°52'11.50" N 97°00'11.30" W elev 814 ft
Graph: Min, Avg, Max: Elevation: 800, 828, 839 ft
Range Totals: Distance: 0.89 mi Elev Gain/Loss: 67.2 ft, -67 ft Max Slope: 33.6%, -29.6%
839 ft
825 ft
800 ft
838 ft
0.8%
Tour Guide
0.25 mi
0.5 mi
0.75 mi


Elevation Profile
Elevation Value (feet)
850
830
810
790

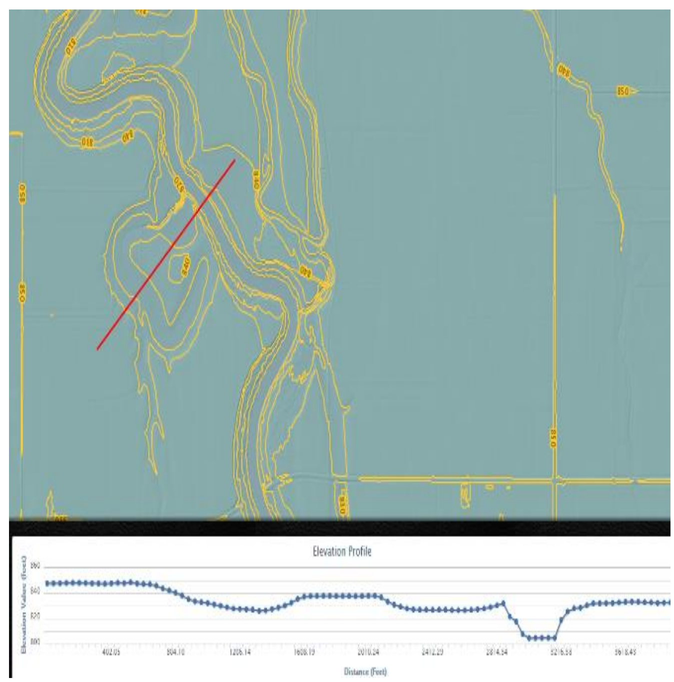

801 ft
651 ft
Cross section 11
© 2015 Google
1991 Imagery Date: 4/2/2012 47°48'58.20" N 96°58'57.33" W elev 831 ft
Graph: Min, Avg, Max: Elevation: 801, 830, 842 ft
Range Totals: Distance: 0.55 mi Elev Gain/Loss: 53.5 ft, -56 ft Max Slope: 38.6%, -49.2%
842 ft
825 ft
801 ft
-0.9%
Tour Guide
0.20 mi
0.30 mi
0.40 mi


Elevation Profile
Elevation Value (feet)
840
820
800


Cross section 12
© 2015 Google
1991 Imagery Date: 4/2/2012 47°47'38.83" N 96°58'03.67" W elev 830 ft eye alt 7174 ft
Graph: Min, Avg, Max Elevation: 802, 827, 843 ft
Range Totals Distance: 0.73 mi Elev Gain/Loss: 72.2 ft, -72.3 ft Max Slope: 34.1%, -27.1%
843 ft
825 ft
802 ft
-0.9%
Tour Guide
0.25 mi
0.5 mi
0.73 mi

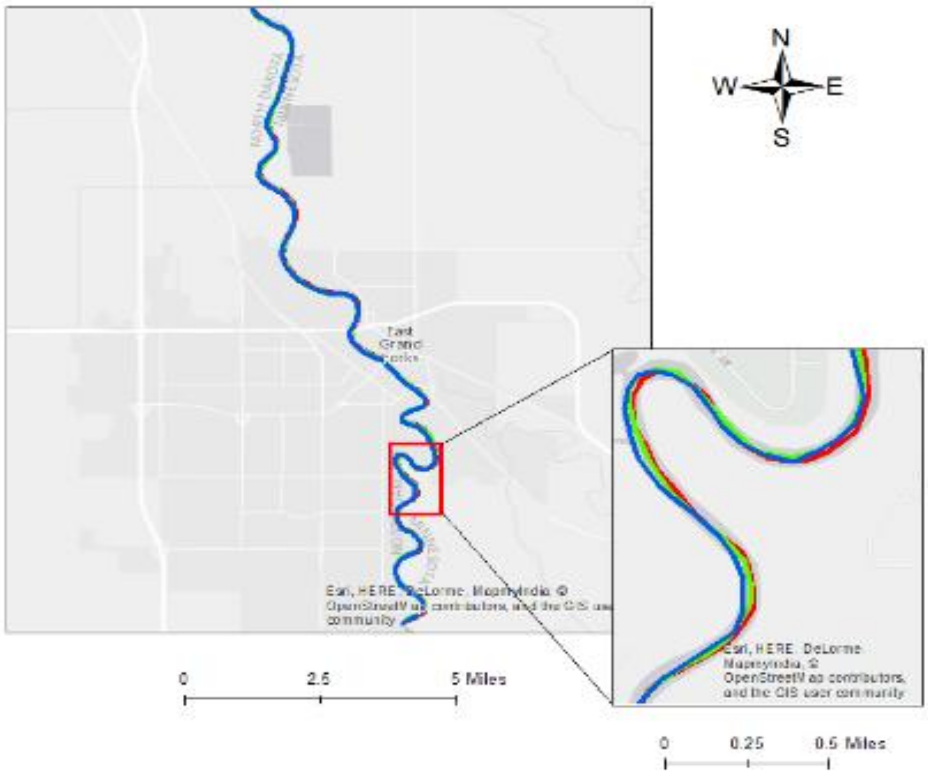

Elevation Profile
Distance (Feet)


Cross Section 13
Tour Guide


Elevation Profile
Distance (Feet)

Appendix C.

Repeat Photography within ArcGIS

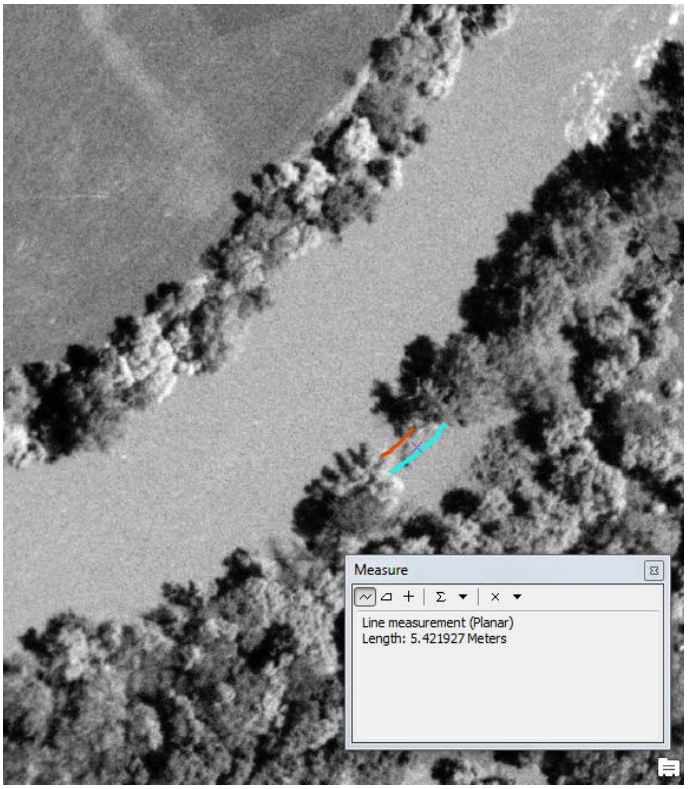


Figure… Image produced in ArcMap using historic images dating back to 1934. Geo- referencing and digitizing techniques used to display a change in the rivers course laterally as see by in the inset map.

Table 1.

Measurement #	Lat	Long	Distance m/yr	Change in 53 yrs	East or West	River Miles
1	47°41'58.28"N	96°54'59.43"W	5.423 meters	.1023 m/ yr.	West cut bank	1.22
2	47°47'50.93"N	96°58'24.49"W	7.911 meters	.1493 m/ yr.	West Cut Bank	13.94
3	47°49'19.15"N	96°58'47.68"W	6.3180 meters	.1192 m/ yr.	East Point Bar	17.18
4	47°53'20.30"N	97° 1'10.39"W	7.0550 meters	.1331 m/ yr.	East Cut Bank	25.1
5	47°54'20.94"N	97° 1'13.14"W	8.368 meters	.1579 m/ yr.	East Cut Bank	27.06
6	48° 3'31.37"N	97° 5'19.12"W	10.3705 meters	.1957 m/ yr.	West cut bank	40.5
7	48° 4'7.43"N	97° 5'50.20"W	6.3290 meters	.1194 m/ yr.	West cut bank	41.31
8	48° 8'9.60"N	97° 7'55.64"W	18.3388 meters	.3460 m/ yr.	East Point Bar	47.65

1962 **2015**


Measure
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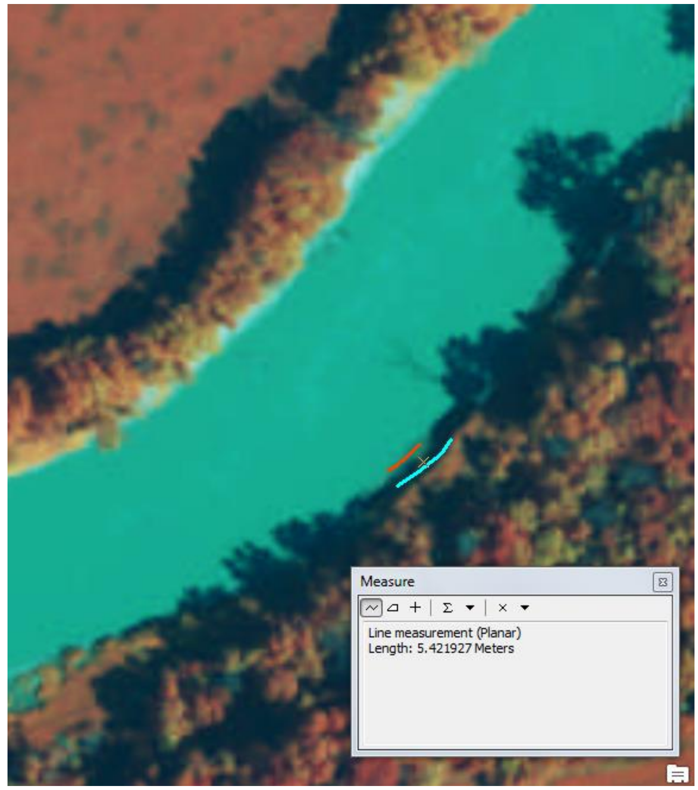
Length: 5.421927 Meters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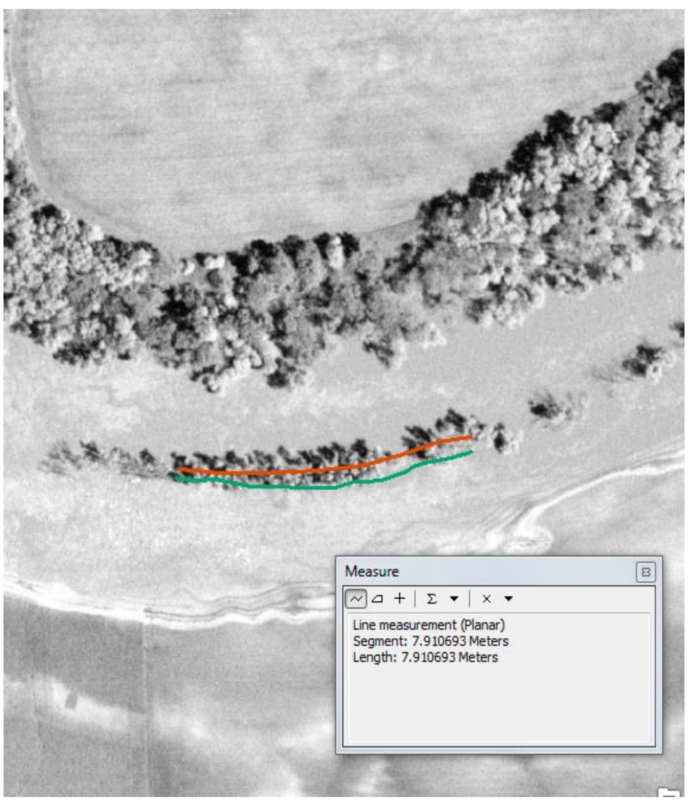
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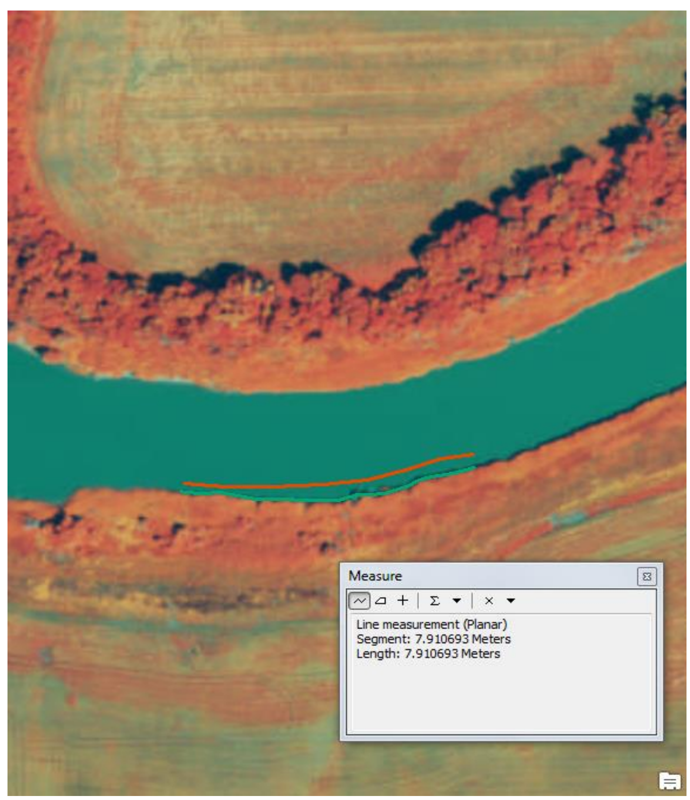
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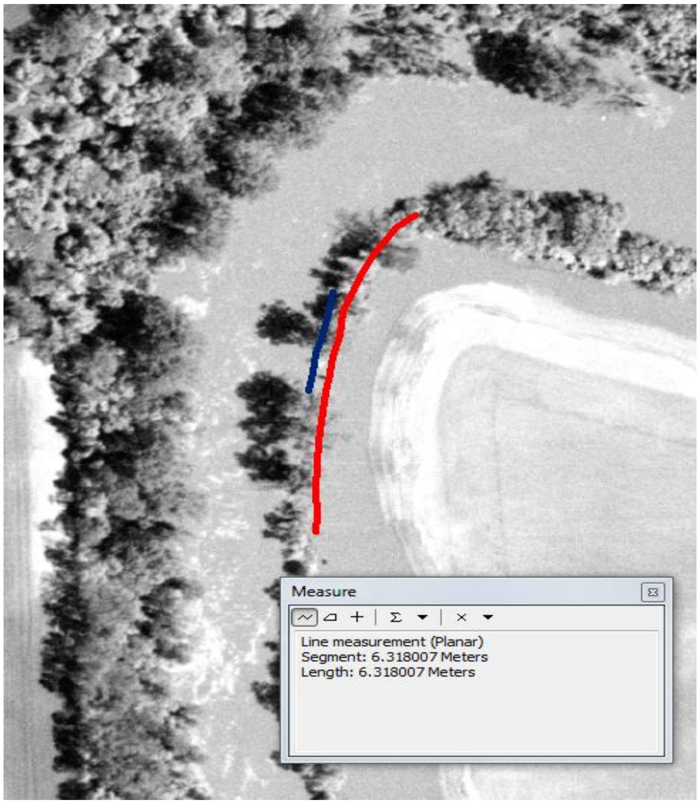
Length: 7.910693 Meters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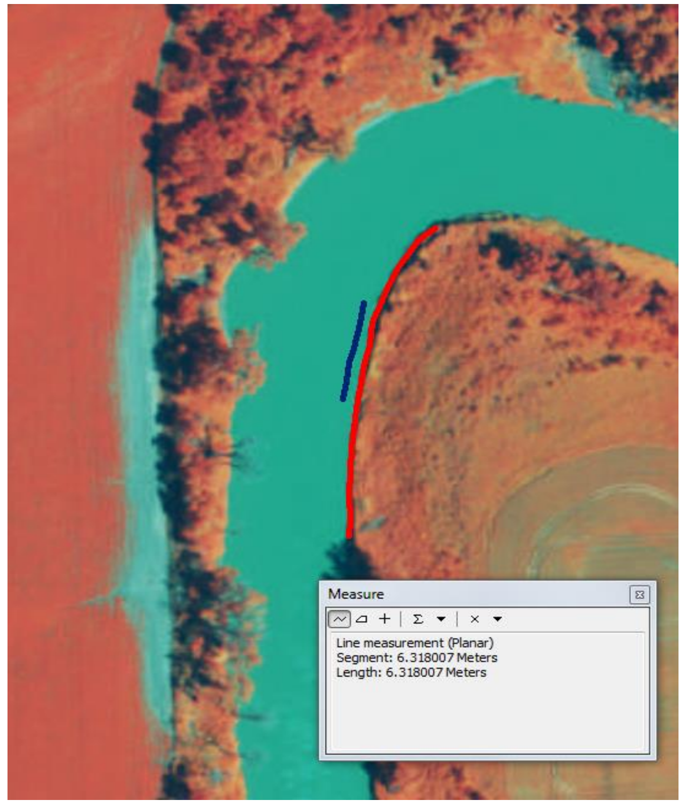
Length: 6.318007 Meters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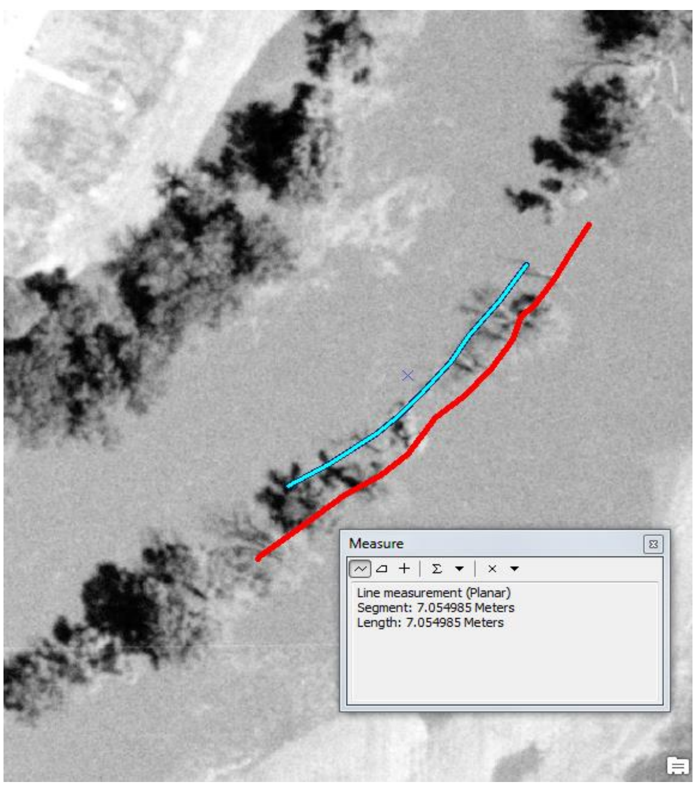
Length: 6.318007 Meters


Measure
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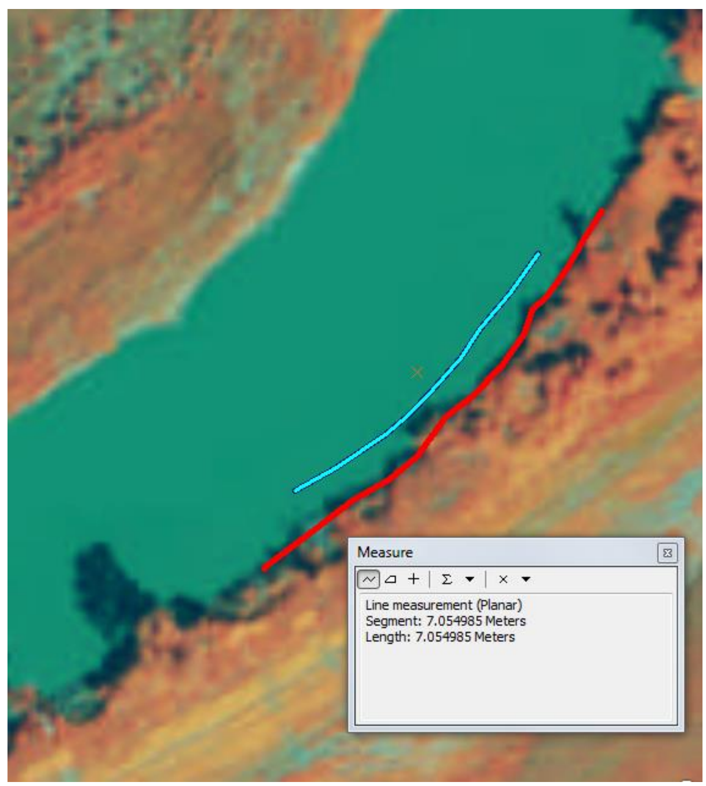
Length: 7.054985 Meters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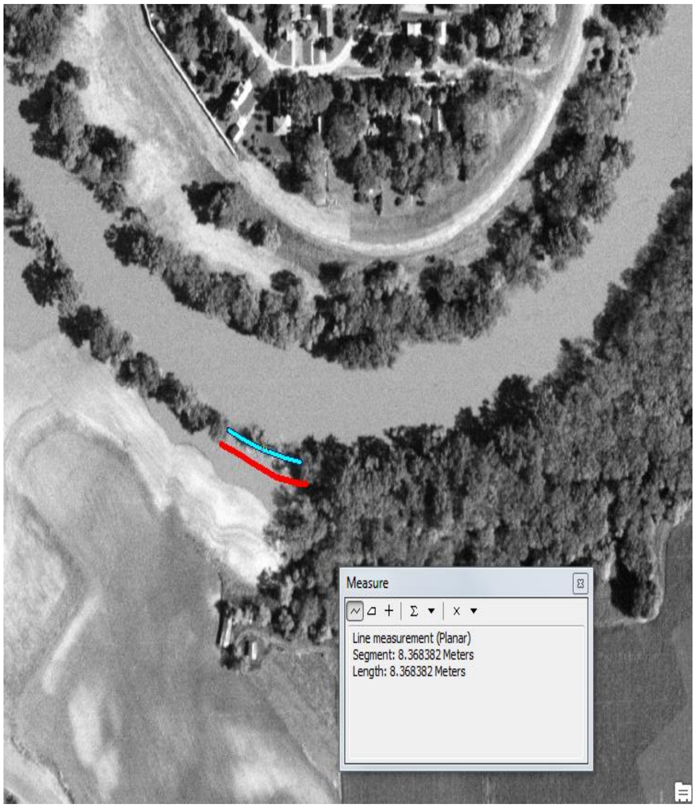
Length: 7.054985 Meters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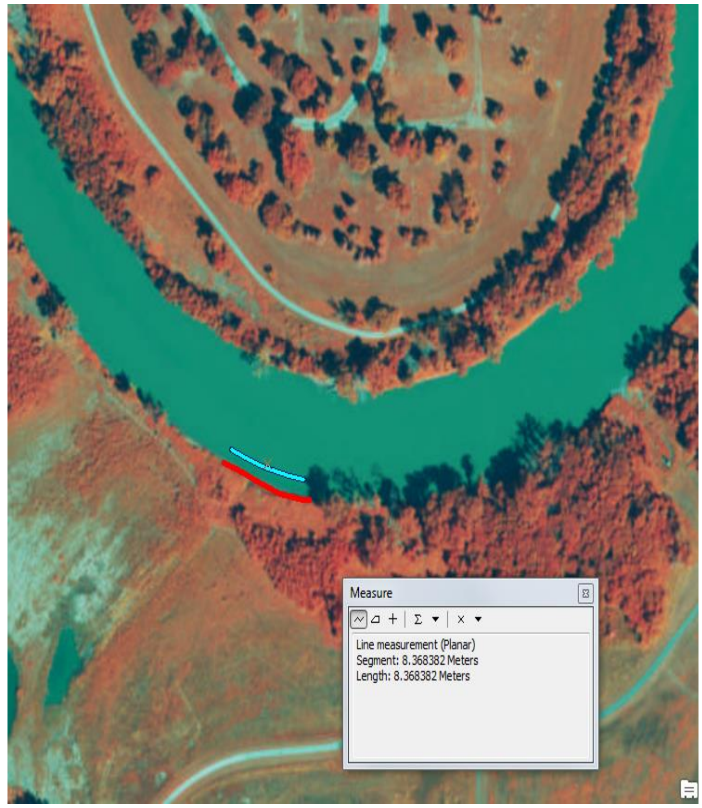
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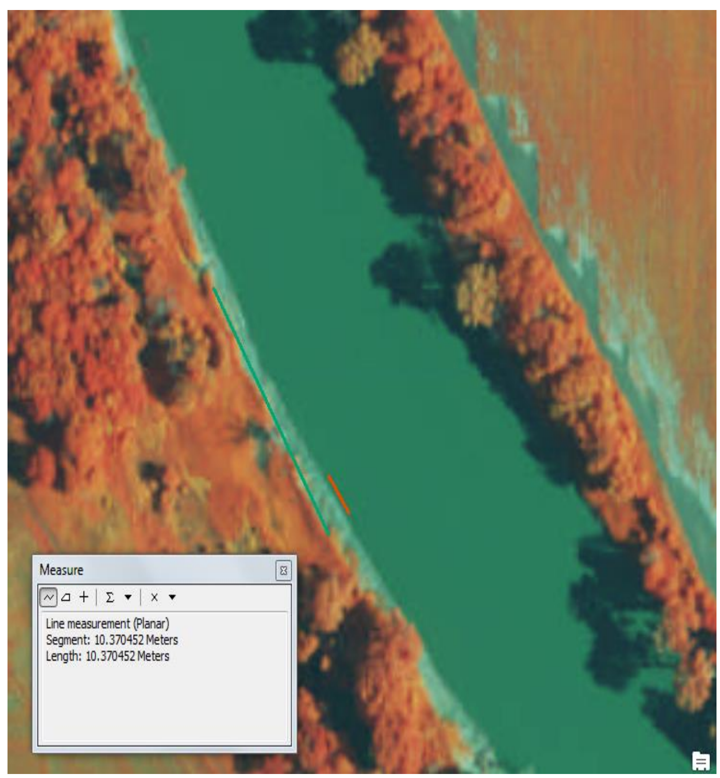
Length: 10.370452 Meters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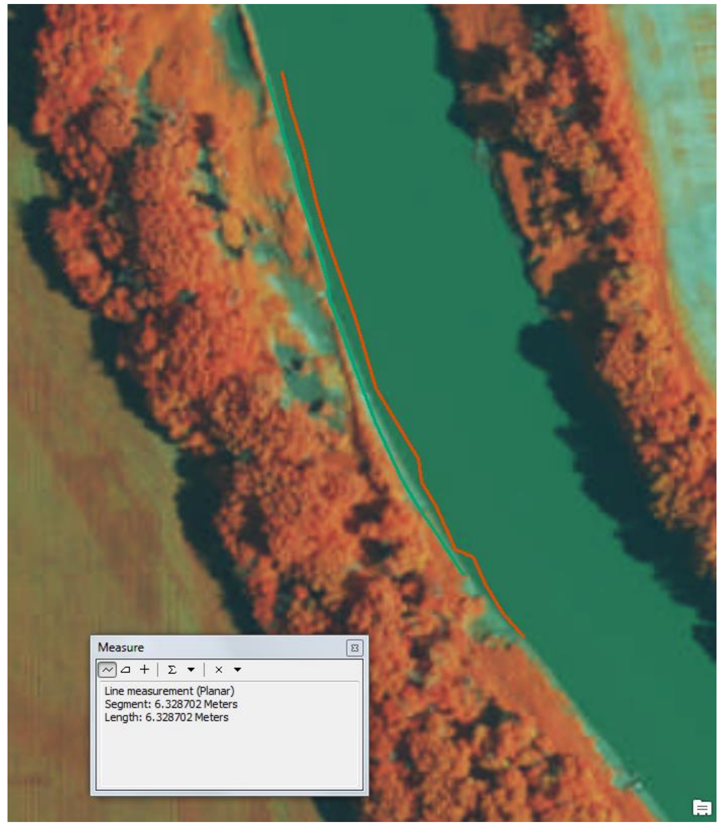
Length: 6.328702 Meters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Length: 6.328702 Meters


Measure
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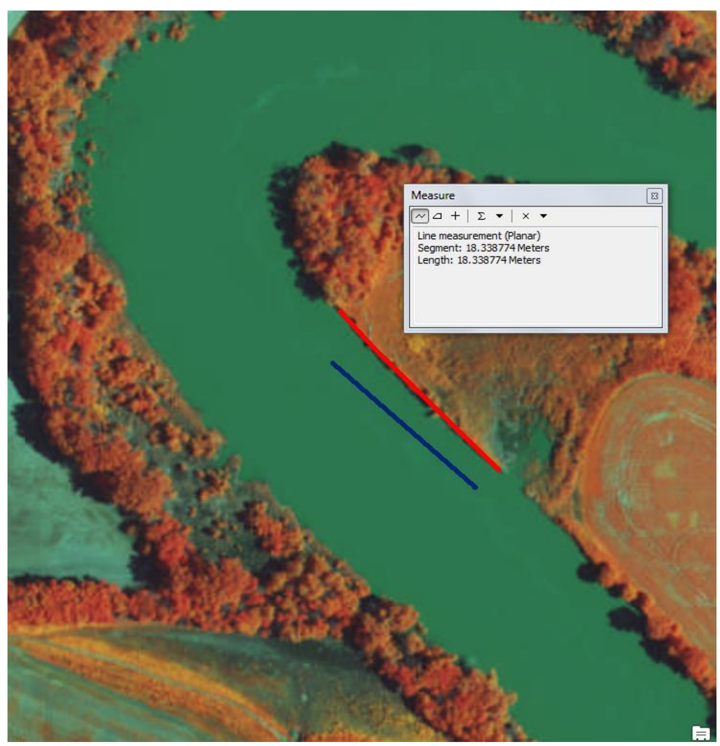
Length: 18.338774 Meters

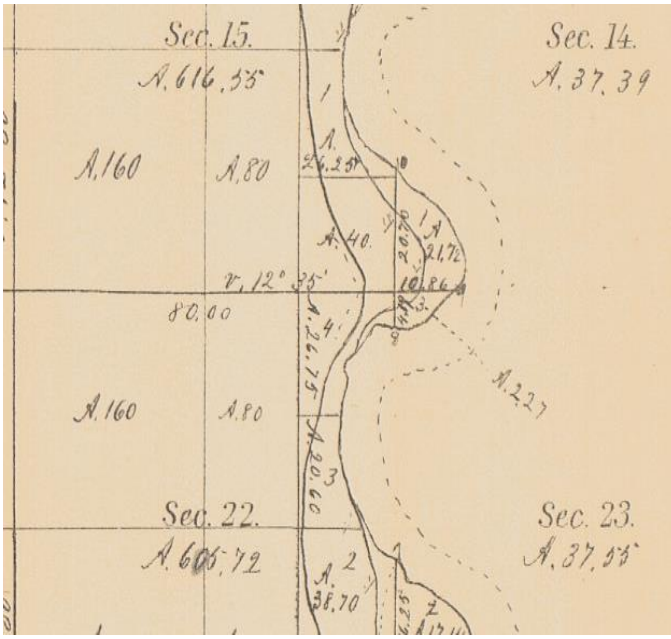

Measure
Line measurement (Planar)
Segment: 18.338774 Meters
Length: 18.338774 Meters

Appendix D.

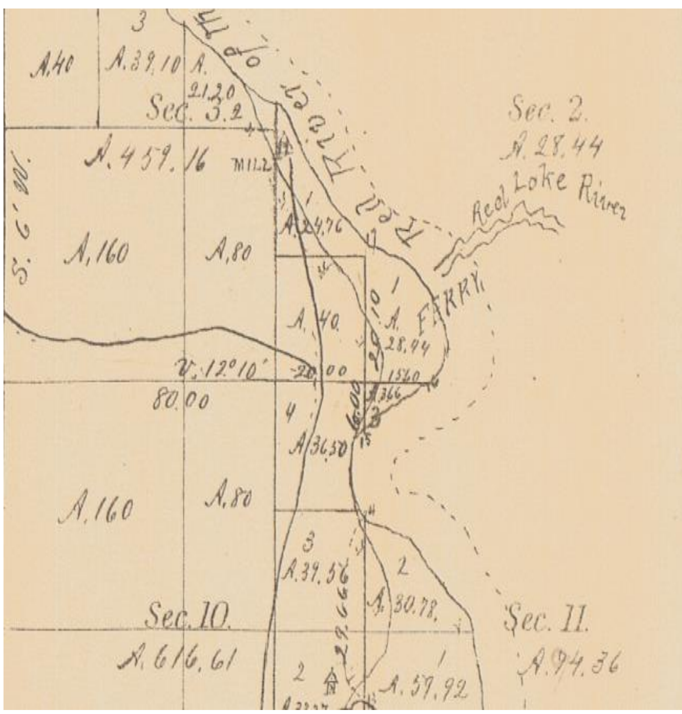
PLAT Maps

Table 1.

Measurement #	Township/ Range	Section	Year of PLAT	Starting Point Coordinates	Location (Due East)	PLAT Measurement (Chain Length)	My Distance	Difference	Change in m/yr.	Migrating
1	Gf City Atlas 151 N, 50W	NW Section 15	1956	47°53'46.08" N 97°01'44.26" W	Belmont Rd. and 130 ft. N of 25th Ave. S	840 ft ± to edge of river = 256.032 meters	819 ft. = 249.63 meters	6.401 meters in 59 years	.1085 m/ year	West
2	Gf City Atlas 151 N, 50W	NW Section 15	1956	47°53'33.05" N 97°01'44.45" W	Belmont Rd. and 320 ft. S of 27th Ave S	1780 ft ± to edge of river = 542.540 meters	1898.98 ft. = 578.81 meters	36.265 meters in 59 years	.616 m/ year	East
3	Online PLAT 151 N, 50 W	SE corner Section 15	1873	47°53'21.87" N 97°01'44.54" W	Belmont Rd. and 32nd Ave. S	30.86 chains= 2036.76 ft to edge of river = 620.805 meters	2215.23 ft. = 675.202 meters	54.398 meters in 142 years	.380 m/ year	East
4	Online PLAT 151 N, 50 W	SE corner Section 3	1873	47°55'06.31" N 97°01'43.58" W	Belmont Rd. and 4th Ave. S	35.60 chains= 2349.6 ft to edge of river = 716.158 meters	2497 ft. = 761.086 meters	44.928 meters in 142 years	.316 m/ year	East
5	Online PLAT 152 N, 50 W	NE corner Section 28	1873	47°57'44.18" N 97°03'58.91" W	N. Columbia Rd. and 40th Ave. N	22.87 chains= 1509.42 ft to edge of river = 460.071 meters	1548 ft. = 471.830 meters	11.759 meters in 142 years	.083 m/ year	East
6	Online PLAT 152 N, 50 W	NW corner Section 16	1873	47°59'28.79" N 97°03'58.93" W	N. Columbia Rd. and 70th Ave. N	45.64 chains = 3012.24 ft to edge of river = 918.131 meters	3045.26 ft = 928.195 meters	10.064 meters in 142 years	.071 m/ year	East
7	Online PLAT 153 N, 50 W	North side Section 7	1873	48°05'31.42" N 97°07'36.54" W	14th St. NE and 29th Ave. NE	60.43 chains= 3988.38 ft to edge of river = 1215.658 meters	3983 ft. = 1214.018 meters	1.64 meters in 142 years	.012 m/ year	West
8	Online PLAT 153 N, 50 W	NW corner Section 6	1873	48°06'23.66" N 97°07'36.46" W	14th St. NE and 30th Ave. NE	11.87 chains= 777.48 ft to edge of river = 236.976 meters	753.34 ft. = 229.618 meters	7.358 meters in 142 years	.052 m/ year	West
9	Online PLAT 149 N, 49 W	North side Section 28	1873	47°42'04.03" N 96°56'17.12" W	5th St.NE and 2nd Ave. NE	60 chains = 3960 ft to edge of river = 1207.008 meters	4101.22 ft. = 1250.056 meters	43.048 meters in 142 years	.303 m/ year	East
10	Online PLAT 154 N, 51 W	SW corner Section 1	1873	48°10'42.41" N 97°08'50.08" W	35th Ave. and 15th St. NE	38.96 chains = 2571.36 ft to edge of river = 783.751 meters	2643 ft. = 805.586 meters	21.835 meters in 142 years	.154 m/ year	East


Sec. 15.
A. 616.55
Sec. 14.
A. 37.39
A. 160
A. 80
A. 160
A. 80
Sec. 22.
A. 605.72
Sec. 23.
A. 37.55


3rd Measurement
Ruler
Line
Path
Pro
Measure the distance between two points on the ground
Map Length:
2,197.70
Feet
Ground Length:
2,198.19
Heading:
90.07 degrees
Mouse Navigation
Save
Clear
©2015 Google


Sec. 3.
A. 459.16
MILL
Red Lake River
FERRY
Sec. 2.
A. 28.44
A. 160
A. 80
A. 160
A. 80
Sec. 10.
A. 616.61
Sec. 11.
A. 94.36


4th Measurement
Ruler
Line
Path
Pro
Measure the distance between two points on the ground
Map Length:
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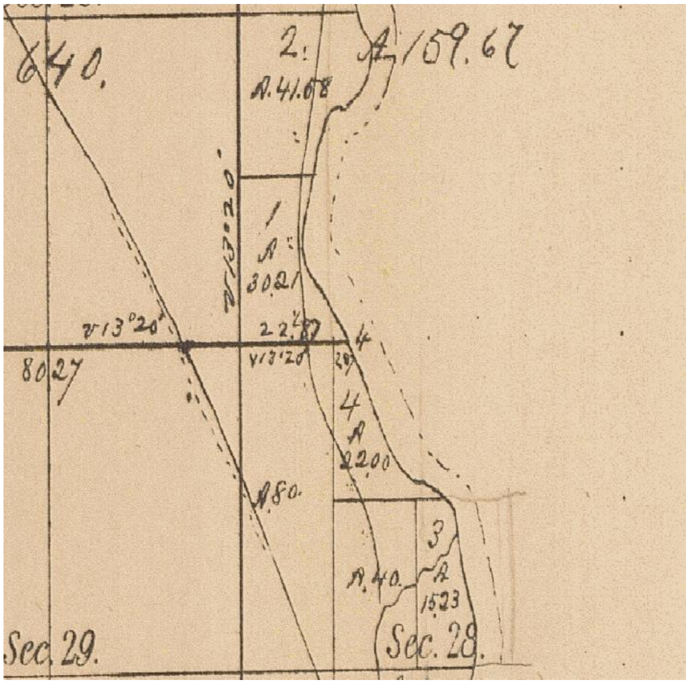
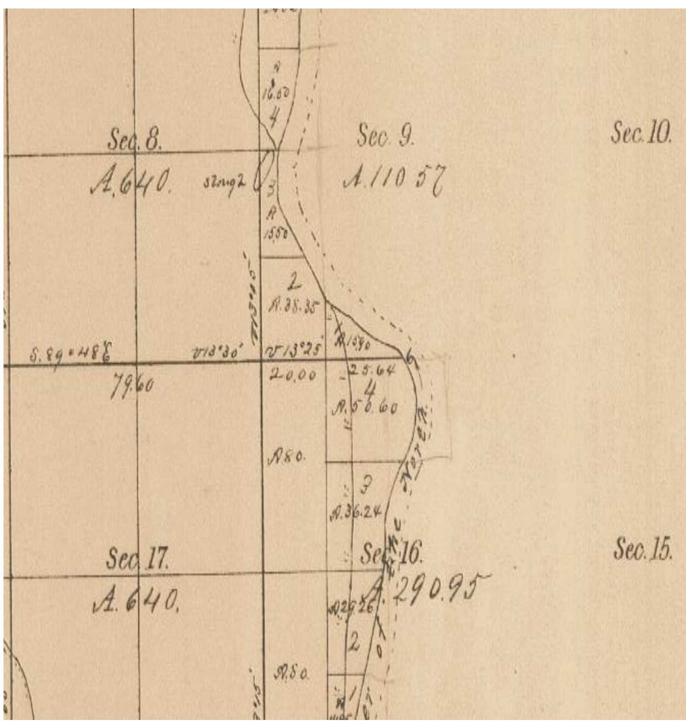
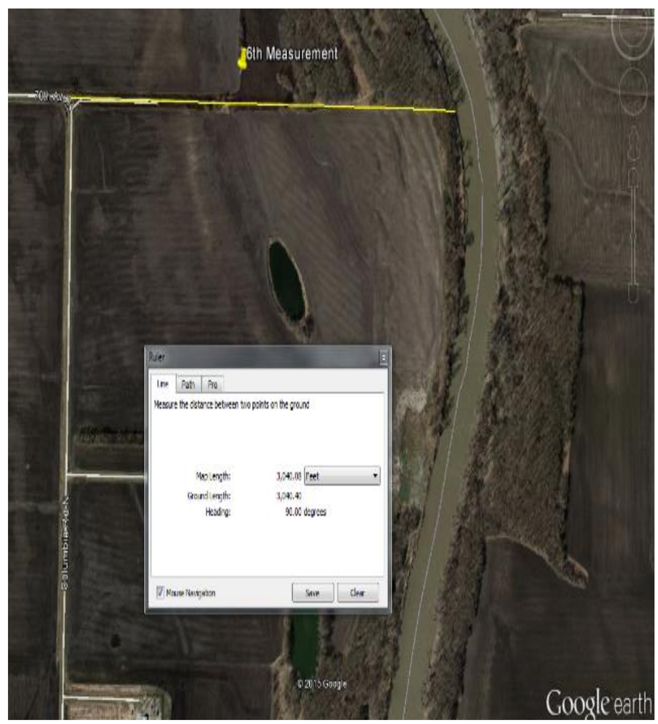
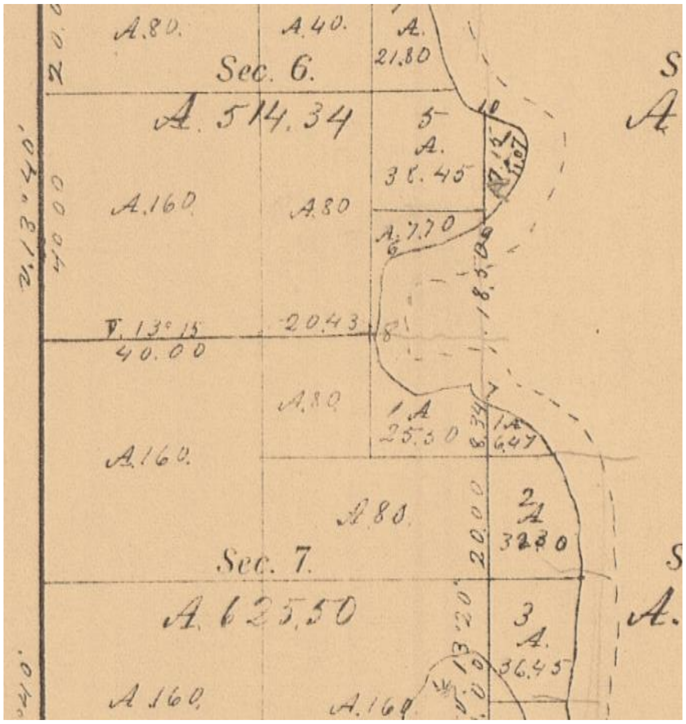
Feet
Ground Length:
2,497.17
Heading:
90.00 degrees
Mouse Navigation
Save
Clear
©2015 Google
Google earth

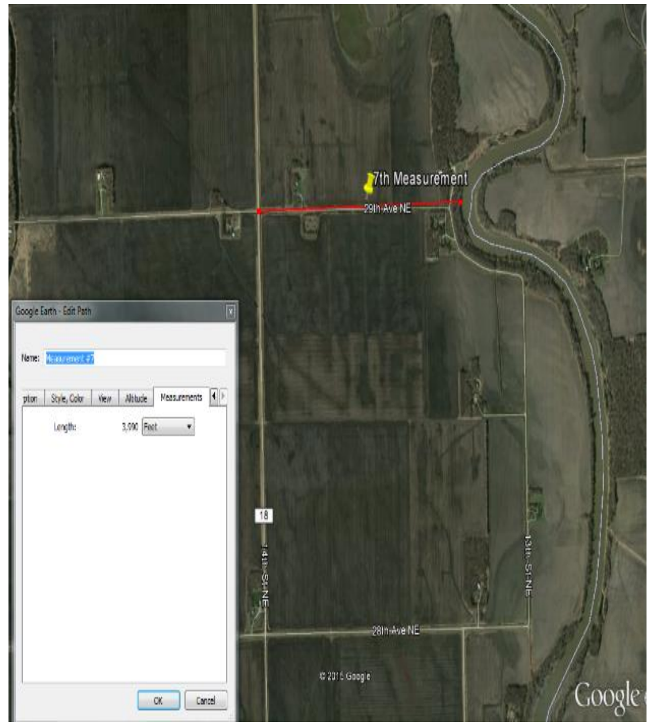

A.159.67
A.41.68
A.30.21
A.22.00
80.27
A.80.
A.40.
A.15.23
Sec. 29.
Sec. 28.

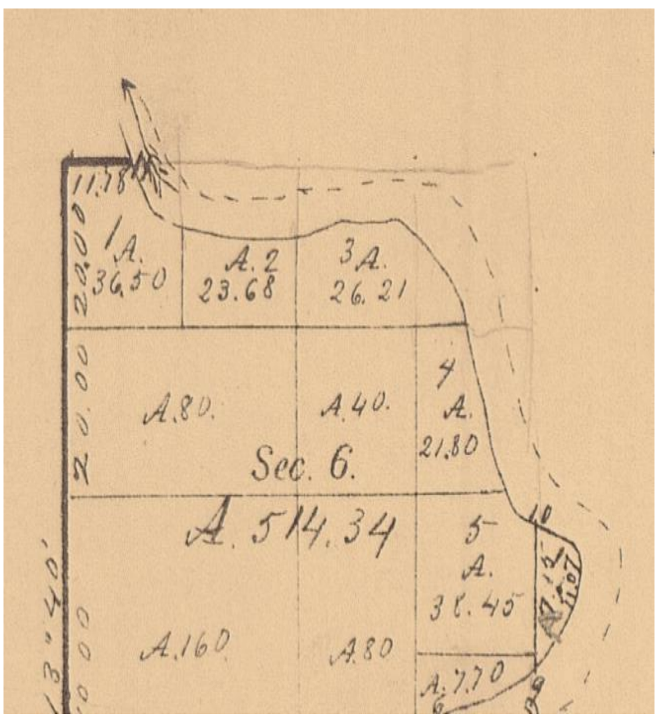

5th Measurement
Measure the distance between two points on the ground
Map Length:
Ground Length:
Heading:
Mouse Navigation
Save
Clear
Google earth

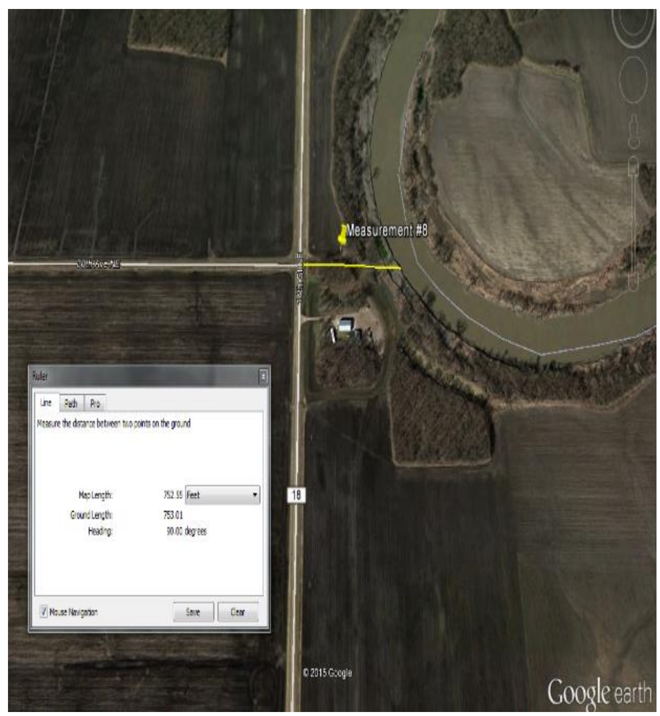

Sec. 8.
A.640.
Sec. 9.
A.110.57
Sec. 10.
A.38.35
79.60
A.56.60
A.80.
A.36.24
Sec. 17.
A.640.
Sec. 16.
A.290.95
Sec. 15.

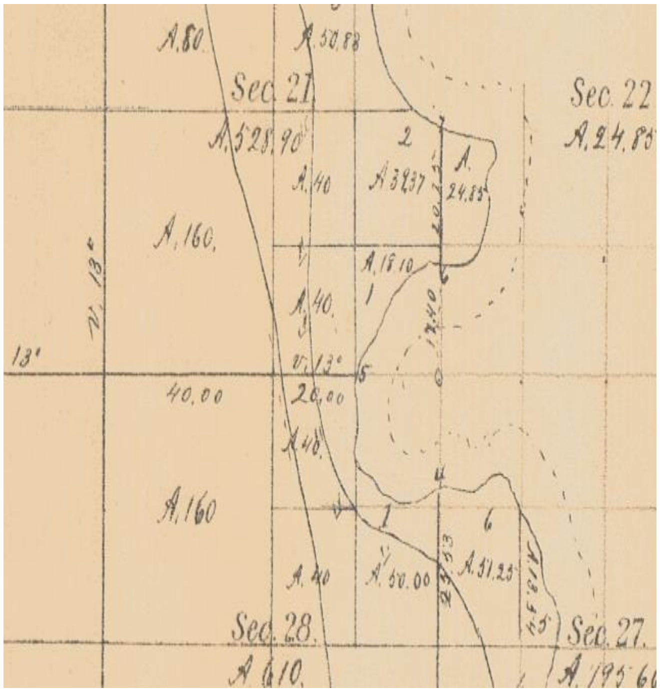

6th Measurement
Measure the distance between two points on the ground
Map Length:
Ground Length:
Heading:
Mouse Navigation
Save
Clear
Google earth

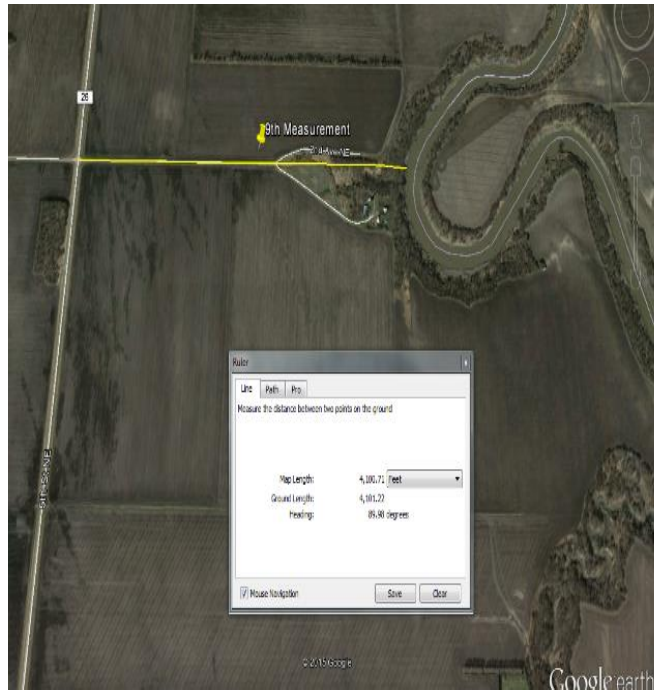

Sec. 6.
A. 514.34
A.160
A.80
Sec. 7.
A. 625.50

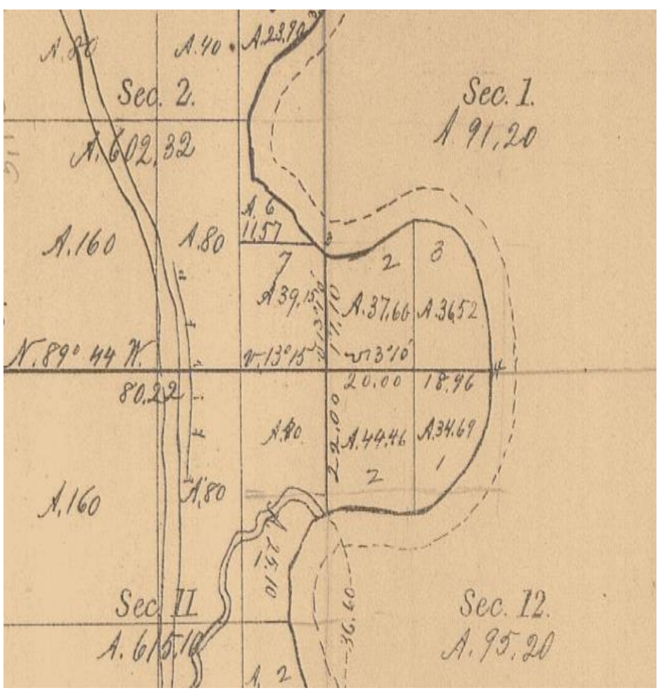

7th Measurement
29th Ave NE
Length:
Feet
OK
Cancel
18
Google


A.2
23.68
3 A.
26.21
A.80.
A.40.
Sec. 6.
A. 514.34
A.160
A.80


Measurement #8
Ruler
Map Length:
Ground Length:
Heading:
Save
Clear
18
Google earth


Sec. 21
A. 528.90
Sec. 22
A. 24.85
A. 160.
A. 160
Sec. 28.
A. 610.
Sec. 27.
A. 195.60


9th Measurement
Ruler
Line
Path
Pro
Measure the distance between two points on the ground
Map Length:
4,180.71
Feet
Ground Length:
4,181.22
Heading:
89.98 degrees
Mouse Navigation
Save
Clear
Google earth


Sec. 2.
A. 602.32
Sec. 1.
A. 91.20
A. 160
N. 89° 44 W.
80.22
A. 160
Sec. 11
A. 615.10
Sec. 12.
A. 95.20


10th measurement
Ruler
Line
Path
Pro
Measure the distance between two points on the ground
Map Length:
2,642.05
Feet
Ground Length:
2,642.30
Heading:
90.02 degrees
Mouse Navigation
Save
Clear
Google